DESIGNING NAVAL SURFACE SHIPS FOR SPEED

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by

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ABSTRACT

An investigation of the design of naval surface ship hulls and the impact of hull form on other performance features is undertaken.

The elements of resistance are identified and discussed.

Fourteen hull form parameters, sufficiently descriptive for design are selected. There mutual interdependence is noted. The correlation with the resistance coefficient, C_{TL} and the hull form parameters, as well as the hydrodynamics involved is discussed.

Performance features other than calm water speed are presented and their dependence on hull form discussed.

A low resistance hull form is selected and the resulting impact on the other performance features is estimated.

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NOMENCLATURE

A_A = TOTAL SECTION AREA AT THE AP

A_B = TOTAL SECTION AREA AT THE FP

AP = AFTER PERPENDICULAR

A_x = TOTAL SECTION AREA AT THE STATION OF MAXIMUM AREA

B_x = BEAM AT THE STATION OF MAXIMUM SECTION AREA ON L_{WL}

$C_T = R_T/\frac{1}{2}\rho SV^2$

$C_{TL} = R_T L_{WL}/\Delta V^2$

CF = POSITION OF THE LONGITUDINAL CENTER OF FLOTATION MEASURED FROM THE FP

$C_p = \nabla/(L_{WL}A_x)$

$C_x = A_x/(B_x T_x)$

$f_A = A_A/A_x$

$f_B = A_B/A_x$

FB = POSITION OF THE LONGITUDINAL CENTER OF BOUYANCY MEASURED FROM THE FP

FP = FORWARD PERPENDICULAR

$F_\nabla = V/\sqrt{g\nabla^{1/3}}$, VOLUME FROUDE NUMBER

i_B = ANGLE OF THE BUTTOCK AT $\frac{1}{4}$ T_W AT STATION $L_{WL}/20$ FORWARD OF THE AP

i_E = ENTRANCE ANGLE MEASURED BETWEEN THE CENTERLINE AND A TANGENT TO THE DESIGNER'S WATERLINE AT THE FP

i_R = RUN HALF-ANGLE OR ANGLE OF THE WATERLINE

L_{WL} = SHIP OR MODEL LENGTH MEASURED ON THE DESIGNER'S WATERLINE

PC = PROPULSIVE COEFFICIENT

R_T = TOTAL RESISTANCE OF THE HULL IN POUNDS

S = WETTED SURFACE

Ⓢ $= S/\nabla^{2/3}$

SFC = ALL PURPOSE FUEL CONSUMPTION RATE, $lb_f/(SHP\ HR)$

SHP = SHAFT HORSEPOWER

T_t = TRANSOM DRAFT AT THE AP

T_W = TRANSOM WIDTH AT THE AP

T_x = DRAFT MEASURED FROM THE DESIGNER'S WATERLINE TO THE LOWEST POINT OF THE STATION OF MAXIMUM AREA

V = SHIP SPEED IN KNOTS

Δ = DISPLACEMENT IN TONS

∇ = VOLUME OF DISPLACEMENT IN CUBIC FEET

$\underline{\Delta}$ = $\Delta/(.01 L_{WL})^3$, DISPLACEMENT-LENGTH RATIO

1. INTRODUCTION

Naval ship operators have, for several years, been asking why our surface combatants have not been achieving a greater speed capability. They have observed displacement, weapons effectiveness and other performance features improve while speed has not changed significantly.(figure 1.).

Through what method or device can the speed of a bouyancy supported vessel be increased? From the equations for calculating effective and shaft horsepower.

$$EHP = R_t/\Delta \cdot \Delta \cdot V, \text{ and} \tag{1}$$

$$SHP = EHP/PC, \text{ therefore} \tag{2}$$

$$V = SHP\ PC/(\frac{R_t}{\Delta})(\Delta) \tag{3}$$

one can see that speed can be increased by improving the hull form so that R_t/Δ decreases or by decreasing the size of a ship so that Δ is decreased. Alternatively, given a specific hull form and size, the speed can be increased by increasing the installed horsepower. The installed horsepower can be increased by packing more horsepower in the same volume and with the same weight by an increase in the power density. If horsepower is increased utilizing the same power density additional space and weight must be allocated to the propulsion plant. However, even if the installed power can be increased, one has the problem of delivering the additional power to the water. Thus the third alternative for increasing speed is improving the propulsive efficiency (propulsive coefficient). But the propulsive efficiency is a function of both hull form(in terms of wake fraction and thrust deduction) and propulsive device.

One can observe in figure 1 that displacement has increased at a faster rate than propulsive power. Since R_t/Δ and P.C. have remained relatively constant, then, from equation 3, speed can only decrease.

From a typical speed-power curve(figure 2) one can estimate the relative effect of the three alternatives on speed. Near the high speed end of the curve, one finds that a 10% improvement in propulsive efficiency yields only a 1.6% increase in speed. A 10% decrease in hull resistance per ton or a 10% decrease in displacement yields a 2% increase in speed. Since the power curve is somewhat flatter at lower speeds a greater increase in speed could be realized for the same power with a 10% improvement in propulsive efficiency or a 10% decrease in R_t/Δ or Δ.

Considering further the effect of reducing R_t/Δ for constant displacement or reducing Δ with constant R_t/Δ, one finds (figure 3) that if the drag(R_t) could be reduced by 50% in the 30 knot speed range a 16% increase in speed(about 4 knots) is possible.

Note that at 50 knots for the 75% drag case in figure 3 over 200,000 shaft horsepower is required; about the same power as currently installed in aircraft carriers. This power level could perhaps be achieved by increasing the power plant density or using the space and weight assigned to payload and other performance features. Increasing the density has little impact on the rest of the ship but will result in a decrease in reliability due to lower maintainability. Whereas removing payload for power plant equipment will of course have a severe impact.

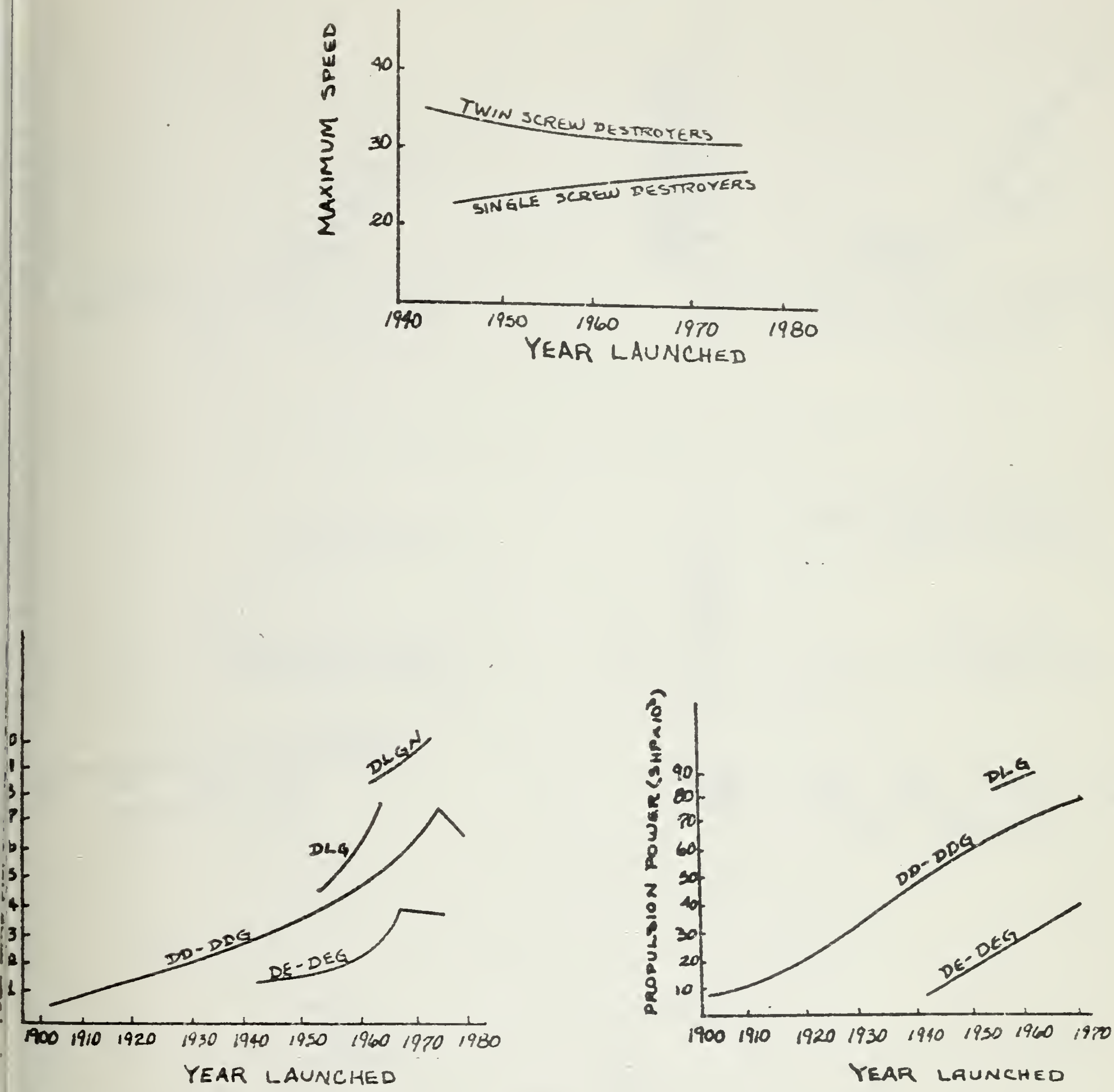


FIGURE 1a. DESIGN TRENDS [11]

Note: Old ship type designations were used in this manuscript. The new designations may be obtained as follows:

DE-DEG → FF-FFG
DL-DLG → CG.

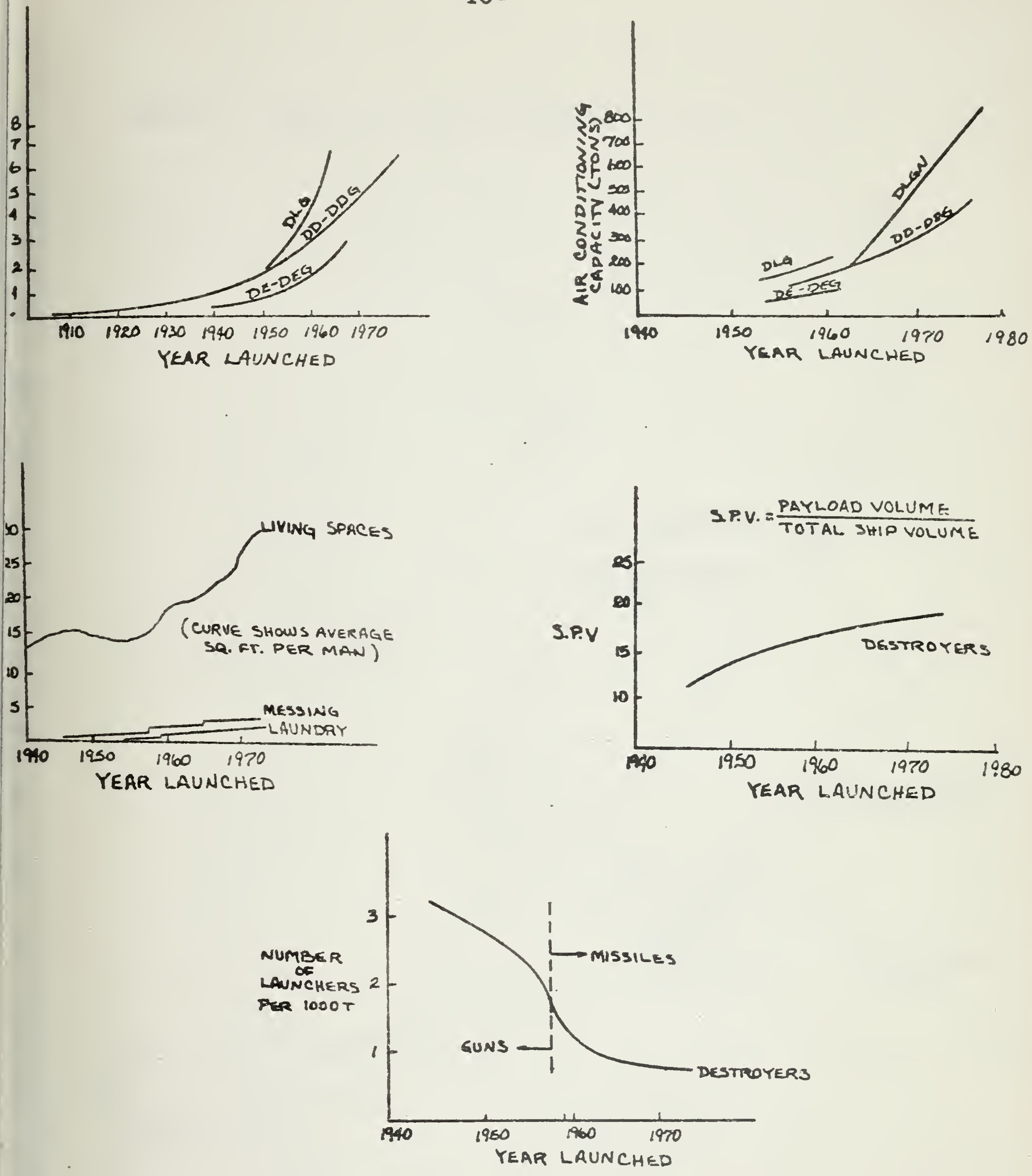
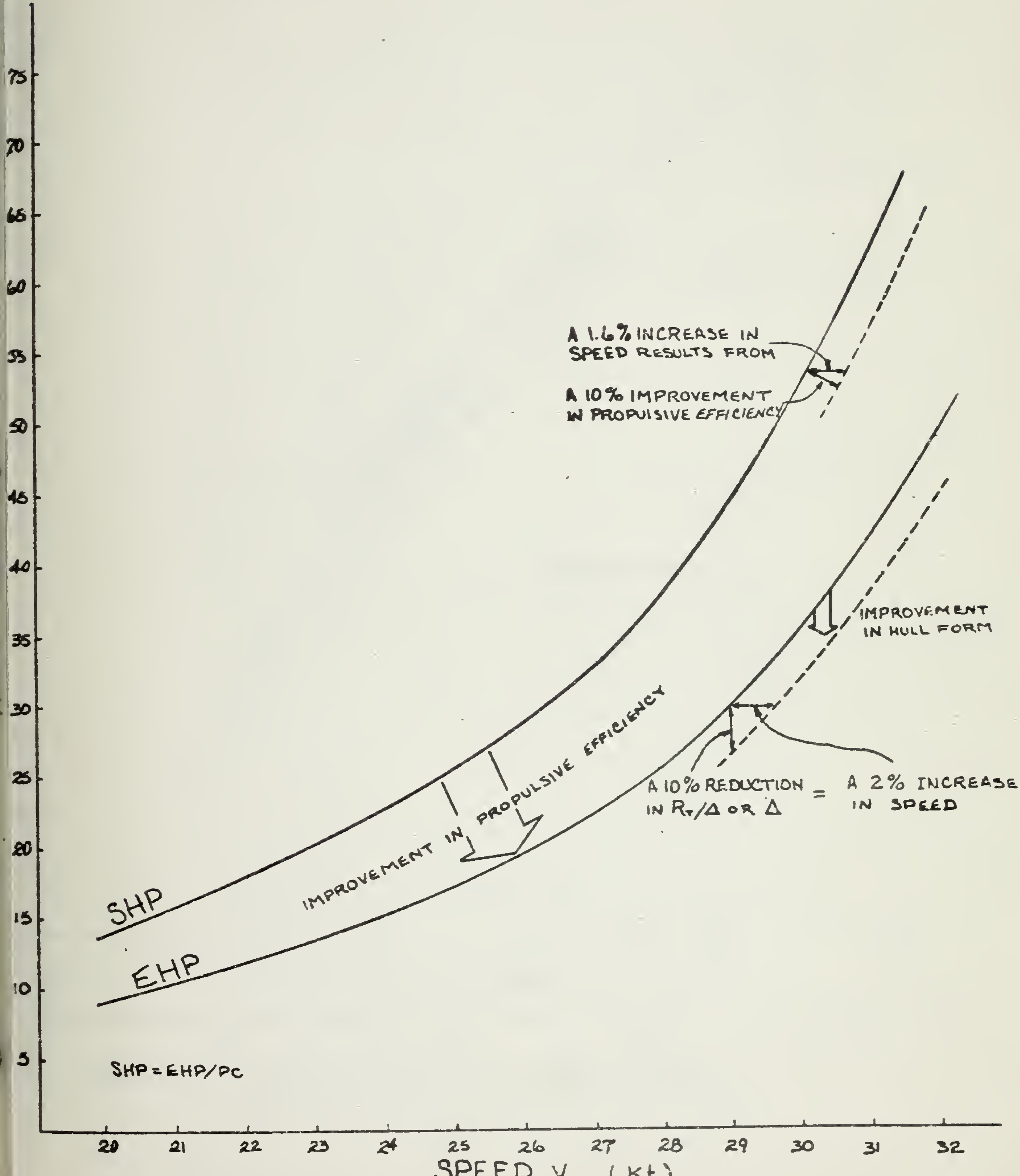


FIGURE 1b, DESIGN TRENDS (CONT'D)

FIGURE 2. TYPICAL DESTROYER SPEED-POWER CURVE
FOR A 9000 TON FRIGATE



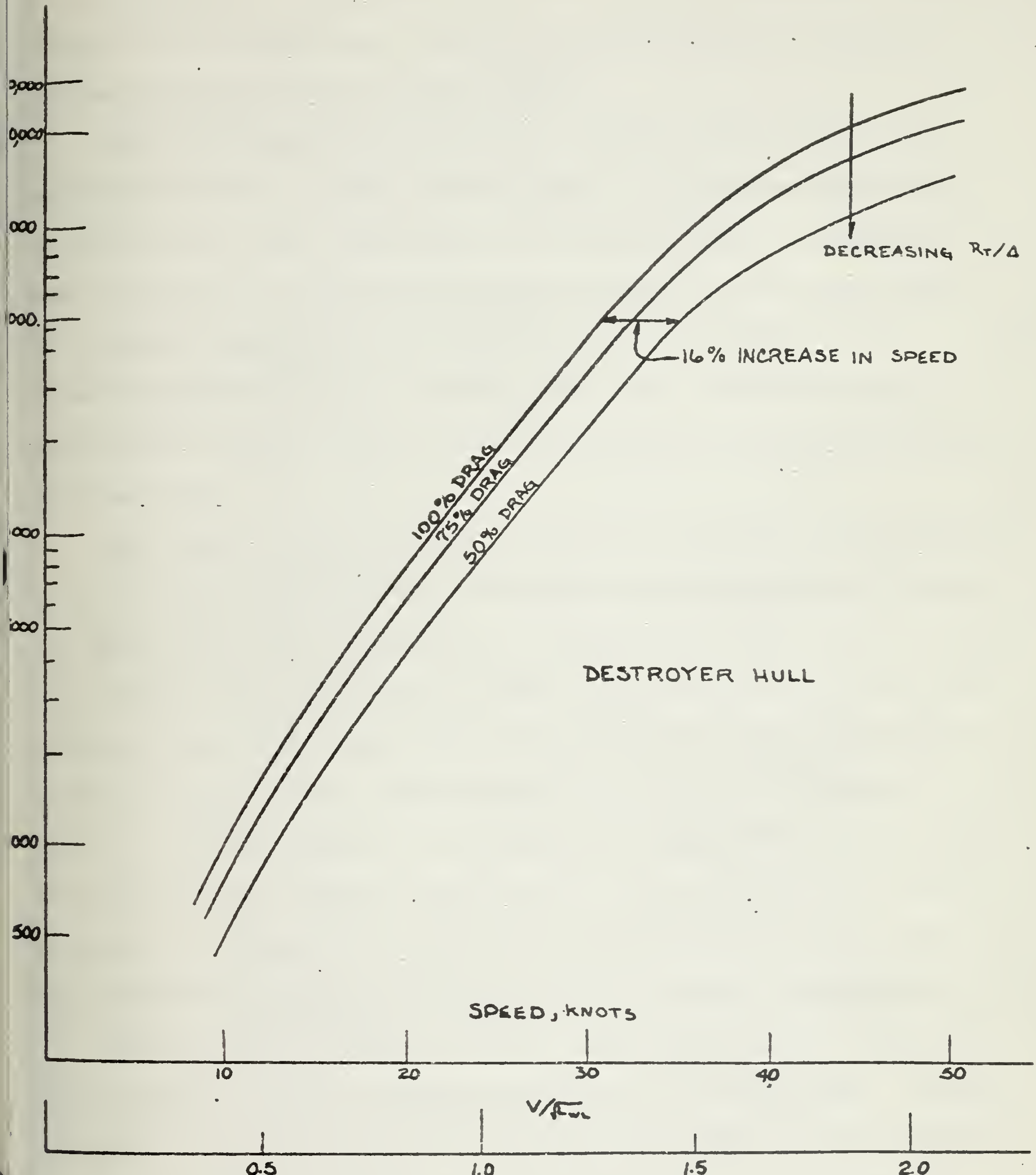


FIGURE 3. THE EFFECT OF REDUCED DRAG ON SHAFT HORSEPOWER AS A FUNCTION OF SPEED [15]

The three alternatives do not have to be considered separately. A truely superior ship would apply the combined effects of improved hull design, power density and propulsive efficiency to achieve significantly greater speeds.

The old adage, "You don't get somethin' for nothin'," is applicable here. A hull form efficient at high speed(Low R_t/Δ) frequently has poor performance at cruising speed. Similarly a high power density propulsion plant may permit very high speeds but operate inefficiently at anything less than full power, penalizing endurance for constant fuel load. However proper power plant design, using multiple propulsion units may minimize this problem.

The effect of hull form on propulsive efficiency is uncertain. Over the years considerably different hull forms have had nearly the same propulsive efficiency. It would seem then that the only opportunity for significantly improving propulsive efficiency in surface ships is by improving the efficiency of the propulsive device. Typical fixed pitch propeller efficiencies decrease rapidly with any change in ship speed or shaft RPM, from a peak of 65%-70% under specific conditions. Although there are other propulsion devices, the controllable pitch propeller may offer the greatest opportunity for efficient off-design performance.

This thesis attempts to treat comprehensively the improvement in speed possible through improved hull form design. Those elements of the hull form that impact the powering requirements will be defined and discussed. Finally, the cost of designing for maximum speed in terms of the other ship performance features

will be investigated.

As will become evident, a ship's underwater hull form is often a compromise between conflicting requirements. The compromise in hull form may be extended even beyond the basic hydrodynamic characteristics of the hull; such is the case in the frequent choice of a fuller hull form in order to provide additional volume in the ship. This is a compromise dictated by the fact that modern destroyers are volume limited and not weight limited. The basic hydrodynamic characteristics also force a compromise in hull form due to the change in relative importance of the components of resistance resulting in efficient performance in one speed range and inefficient performance in another.

2. Hull form Design

Although thousands of ships have been designed and built, and a great number of ship models have been tested and studied, a complete understanding of ship hydrodynamics is still lacking. What quality or qualities a good ship must possess to have a superior resistance performance as well as excellent propulsive characteristics is still not completely known. Under typical circumstances, a ship designer would normally try to find an existing ship with a good performance record to use as a basis for his new design. The term "parent form" fully describes the current practice in ship design.

Naval ship design has followed this practice. Designs have tended to be evolutionary with no significant departure from parent forms. If the operating community indicates a need for a new class of destroyers with certain requirements, the technical community begins a review of existing destroyers to find a baseline or "parent form" for a starting point in the design spiral. One consequence of this design approach has been no significant improvement in hull efficiency in terms of R_t/Δ.

This raises a number of questions. Why have ship designers not deviated from this practice? Is this the best that can be done? If one is willing to deviate significantly, what can be gained and at what price? How does one begin and what design philosophy will yield the desired results of high speed under normal conditions at sea? The answer to the first question is most probably dependent on numerous factors other than naval

architecture. The answers to the latter questions form the basis for this investigation and will be addressed in the following chapters.

2.1 Calm water performance vs seakeeping

Given that a certain amount of power is being delivered to the water by a ship, the speed obtainable is dictated by the drag described by the components of calm water resistance and seakeeping qualities.

The calm water resistance of a ship at a given speed consists of five main components. They are:

(1) The frictional resistance(R_f), due to motion through a viscous fluid.

(2) The wavemaking resistance(R_w), due to the energy that must be supplied continously by the ship to the wave system created on the surface of the water.

(3) The form resistance(R_{form}), due to pressure drag created by a solid mass passing through a fluid.

(4) Eddy resistance(R_e), due to energy carried away by eddies shed from the hull and appendages.

(5) Air resistance(R_a) experienced by the above water part of the hull.

The resistances under 2, 3, and 4 are commonly taken together as residuary resistance(R_R),

$$R_R = R_w + R_{form} + R_e. \tag{4}$$

The total calm water resistance(R_T) is the sum of the above components,

$$R_T = R_f + R_R + R_a. \tag{5}$$

Although each of the components of resistance increase with speed, the relative importance of each changes with speed. Figure 4 shows that at low speeds, resistance is primarily frictional and wavemaking resistance is vanishingly small. But as speed increases, the wavemaking resistance increases in importance while frictional resistance becomes secondary. As a result of these changes in relative importance of the resistance elements, the design speed will dictate generally different types of hull forms(figure 5).

The frictional resistance of a ship is closely defined by its wetted surface(S) and Reynold's number, $R_n = \frac{VL}{\nu}$ as shown in the following equations:

$$R_f = \tfrac{1}{2}\rho V^2 S C_f \tag{6}$$

where,

$$C_f = f(VL/\nu) + \ldots \tag{7}$$

C_f has experimentally defined values that decrease logarithmically with increase in speed and/or length. Thus frictional resistance is sensitive to parameters other than length only to the extent that they cause changes in wetted surface.

Residuary resistance is similarly defined by,

$$R_R = \tfrac{1}{2}\rho V^2 S C_R \tag{8}$$

However C_R is not universally well defined either analytically or experimentally as is C_f.

The typical humps and hollows on a residuary resistance curve as in figure 6 are a result of wave interference effects. When traveling at speeds such that the hull length is of the

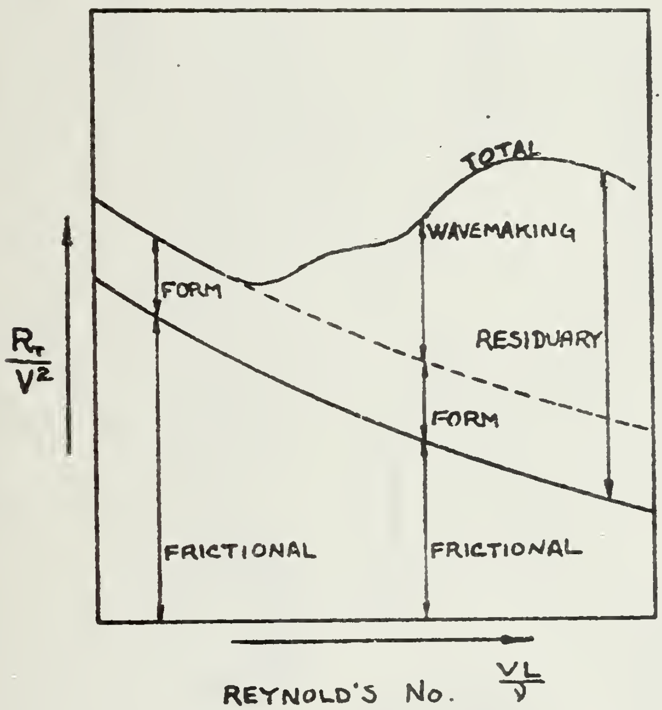


FIGURE 4. RELATIVE IMPORTANCE OF THE ELEMENTS OF SHIP RESISTANCE AS A FUNCTION OF SPEED [6]

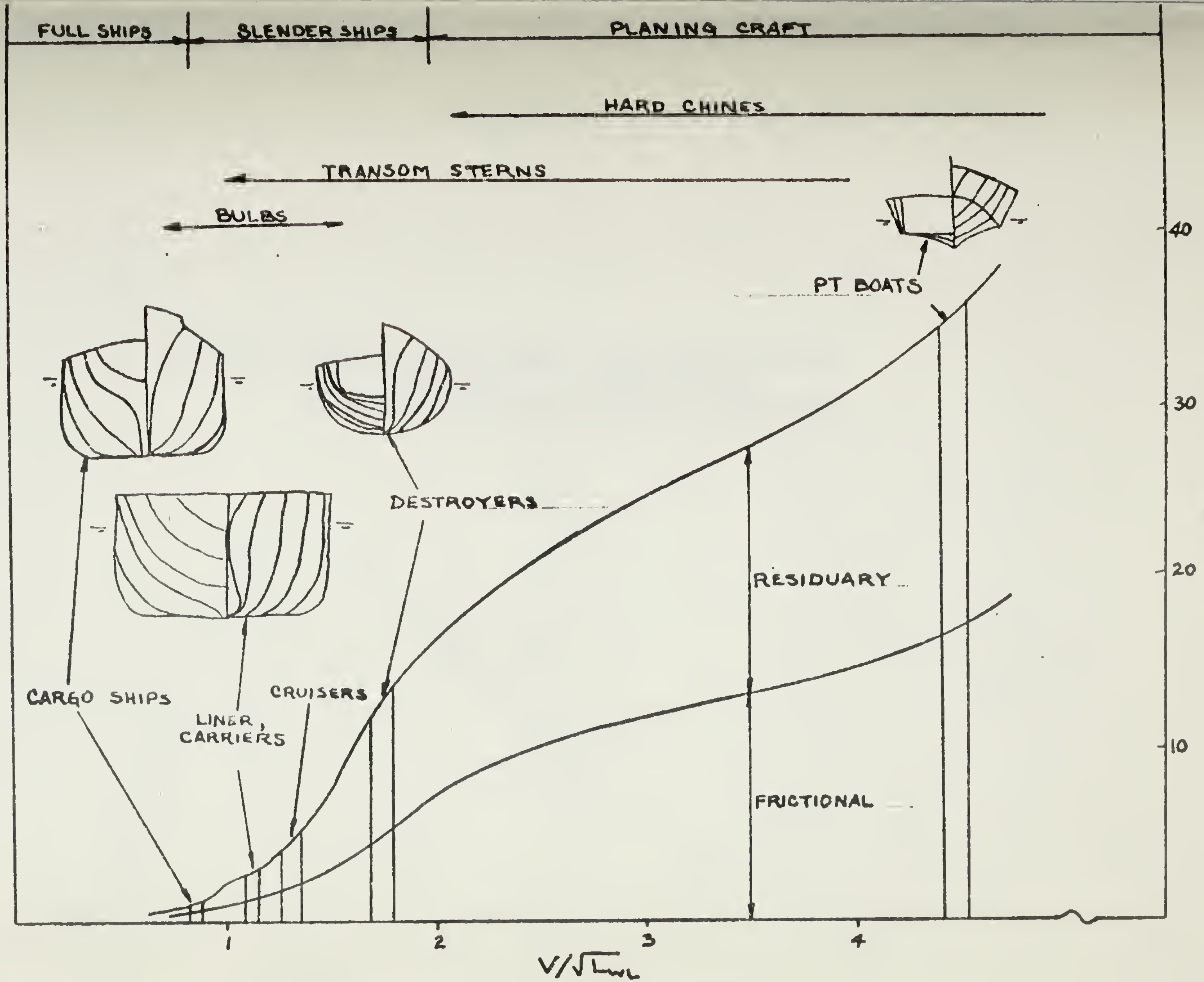


FIGURE 5. HULL FORMS FOR VARIOUS SPEED RANGES [16]

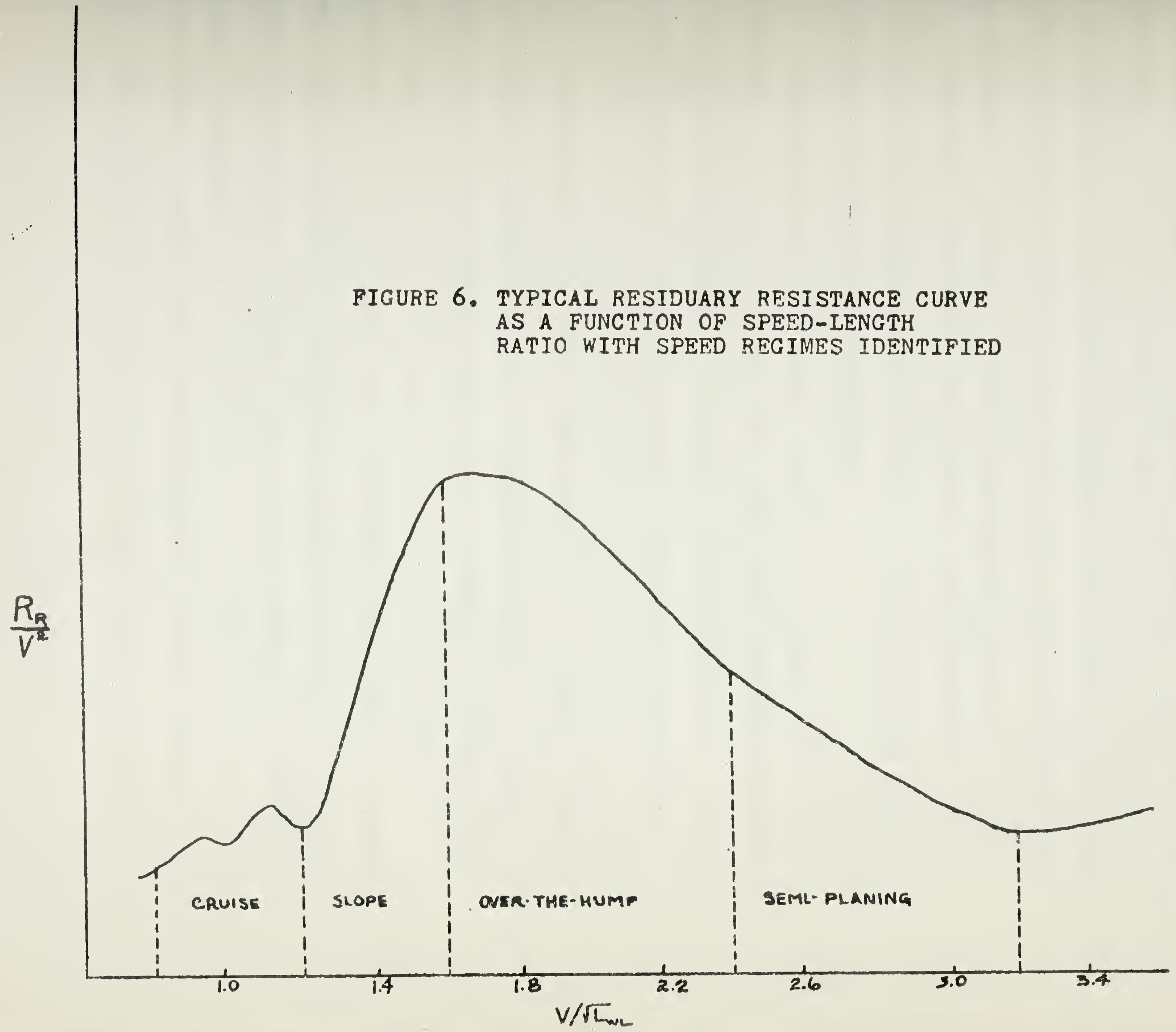


FIGURE 6. TYPICAL RESIDUARY RESISTANCE CURVE AS A FUNCTION OF SPEED-LENGTH RATIO WITH SPEED REGIMES IDENTIFIED

order of 1, 2, 3, 4, ... transverse wave lengths, the resulting wave interference effects of the bow and stern wave systems produce a reduction in resistance since the drag forces from the bow wave are balanced by the thrust forces from the stern wave. However as the speed is changed such that the hull length is a non-integral value of the transverse wave length the bow wave system cancels out part of the stern wave system resulting in an imbalance of forces. Hence the familiar humps and hollows of a residuary resistance curve exhibit the detrimental and beneficial wave interference effects as the increasing speed lengthens the transverse waves[37].

Considering the shape and length of a vessel between the extreme ends, it is a general rule that wave generating pressure disturbances are found at all points or regions along a longitudinal pressure-distribution curve where the curve changes direction. The wave generating intensity may be gaged roughly by the abruptness with which this change of direction occurs. The pressure gradient along the changes in curvature which generates a wave system is sensitive to speed. At low or moderate speeds the wave systems generated at these changes in curvature are vanishingly small compared to the bow and stern wave systems because the pressure gradient is slight. But as speed increases not only do even slighter changes in curvature become wave generating points but the relatively abrupt changes (shoulders) develop significant pressure gradients which contribute noticably to the bow and stern wave systems. Thus at low to

moderate speeds the bulk of the wavemaking is done at the ends of the ship whereas at higher speeds the entire length of the ship contributes to wavemaking.

The residuary resistance then depends on not only the wetted surface but on the local details of the hull form which generate the wave systems, the pressure drag, and the eddies.

Within reason therefore for high speed form design, features of hull form may be selected to minimize residuary resistance and to provide good seakeeping qualities.

The seakeeping qualities of a ship are defined by the severity of motions experienced by a ship in a seaway and the added resistance resulting from encountering waves. The added resistance is largely the result of wave reflection effects and changes in bouyancy distribution. The wave induced motions are characterized by the acceleration experienced in pitch, heave, and roll, slams per hour, deck wetness per hour, and bow emergences per hour. The loss of speed at sea is frequently not the result of insufficient power to overcome the added resistance but a voluntary reduction precipitated by concern for the survival of the ship and comfort of the crew.

Generally speaking, the increased ship resistance or motion in a seaway depend upon hull fineness ratios, section shape, and principal dimensions relative to encounter wavelength i.e., the gross characteristics of the hull. Hence the requirement for good seakeeping performance can be met by specifying tolerable ranges of hull proportions, coefficients, and section shapes in the design conditions of a design effort.

As is discussed in greater detail in Section 4.3, seakeeping qualities are not significantly affected without large changes in dimensions and coefficients, and calm water performance is sensitive to details of the hull form. Therefore if one specifies an appropriate range of coefficients, dimensions and ratios commensurate with the desired seakeeping qualities and other design requirements, the details of hull form can be addressed relative only to calm water resistance.

Given that one needs to address primarily only calm water resistance in developing a hull form with a low power requirement, a means of describing the hull adequately for design purposes using various parameters, and the interaction between these parameters is needed.

2.2 Hull Form Description

The size of a ship as expressed by displacement and length is of course important in determining not only the speed of a ship as indicated in equations 3 and 6, but also in determining the payload carrying ability and other performance features. Since the goal in ship design, from a hydrodynamics viewpoint, is to develop a hull form having a low power requirement, the resulting process in selecting that hull form is by nature a comparative process. A valid comparative process requires the effect of size be eliminated by the use of non-dimensional ratios and coefficients. Fourteen such hull form parameters used to define a ship's hull are presented in Table 1 and defined in the Nomenclature and figure 7.

TABLE 1. HULL FORM PARAMETERS

COEFFICIENT	SYMBOL
1. WETTED SURFACE COEFFICIENT	Ⓢ
2. LENGTH-BEAM RATIO	L_{WL}/B_X
3. BEAM-DRAFT RATIO	B_X/T_X
4. PRISMATIC COEFFICIENT	C_P
5. AREA COEFFICIENT AT STATION OF MAXIMUM AREA	C_X
6. DISPLACEMENT-LENGTH RATIO	$\triangle$
7. POSITION OF LCB FROM THE FORWARD PERPENDICULAR	$\overline{FB}/L_{WL}$
8. HALF ANGLE OF ENTRANCE ON L_{WL}	i_E
9. HALF ANGLE OF RUN ON L_{WL}	i_R
10. BUTTOCK SLOPE	i_B
11. ORDINATE OF SECTION AREA CURVE AT THE FP	f_B
12. ORDINATE OF SECTION AREA CURVE AT THE AP	f_A
13. RATIO OF THE WIDTH OF THE TRANSOM ON L_{WL} TO BEAM AT STATION OF MAXIMUM AREA	T_W/B_X
14. RATIO OF THE TRANSOM DEPTH TO DRAFT AT THE STATION OF MAXIMUM AREA	T_t/B_X

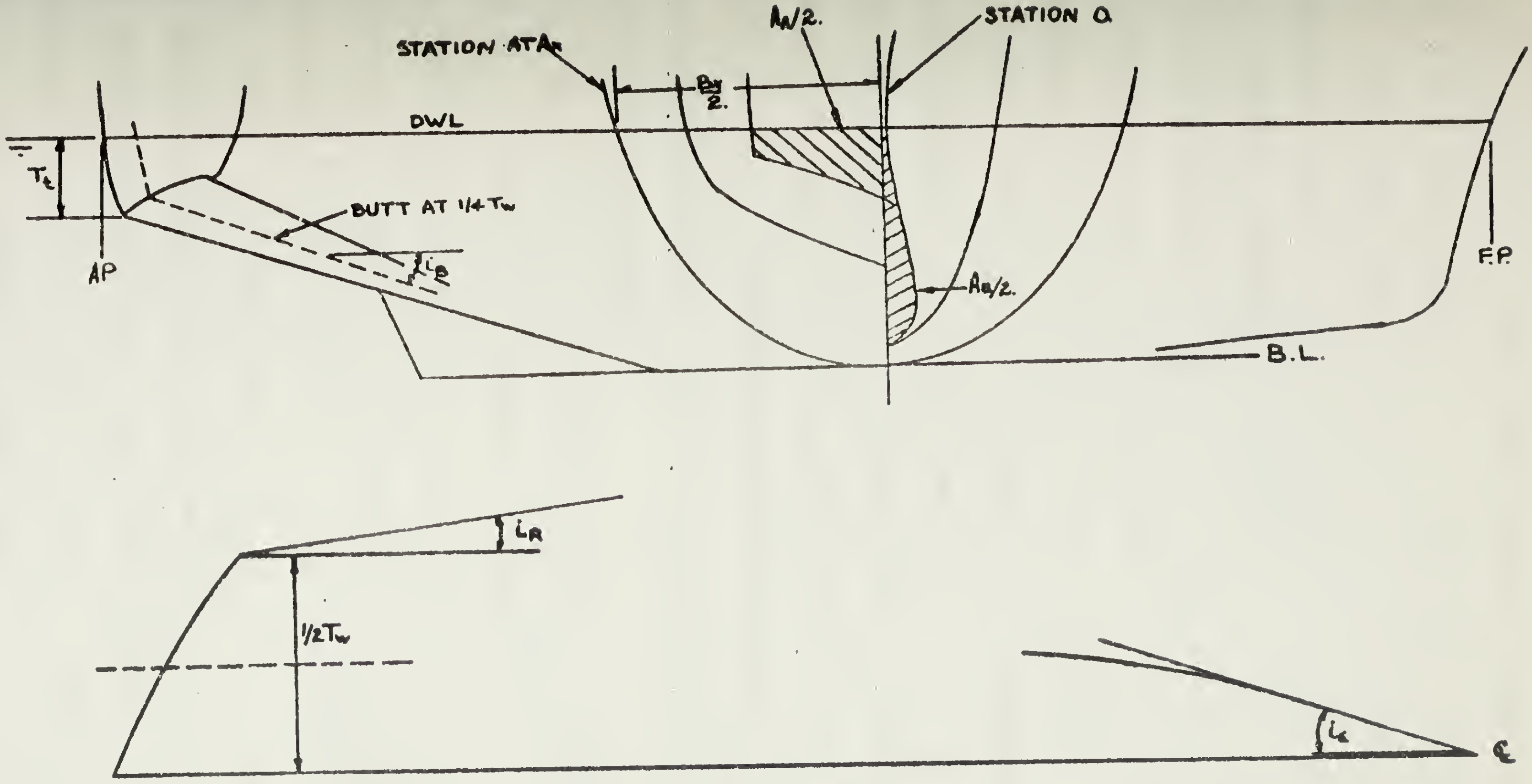


FIGURE 7. DEFINITION OF HULL FORM PARAMETERS

No generally valid relationship between all of these parameters has been obtained for selecting an optimum low resistance hull form. But some success has been achieved in developing equations relating the parameters to resistance at specific speed-length ratios [30, 36, 51].

The problem is that it is difficult to assess the influence of individual hull form parameters. All of the parameters are mutually correlated to one degree or another.

Neal [30] applied a statistical regression analysis to high speed destroyer resistance prediction for 228 models tested since 1900 at the Experimental Model Basin or Taylor Model Basin, now called the Naval Ship Research and Development Center, Carderock, Maryland and in the process developed mathematical correlation coefficients between each of the parameters substantiating the mutual interdependence.

The correlation coefficient, $P_{x_1x_2}$, between two variables x_1 and x_2 indicates the amount of linear association between x_1 and x_2. If $P_{x_1x_2}$ is positive, x_1 is directly proportional(in the statistical sense) to x_2 whereas if $P_{x_1x_2}$ is negative, x_1 is inversely proportional to x_2. The magnitude of $P_{x_1x_2}$ indicates the extent of association. $|P_{x_1x_2}| = 1.$ implies perfect positive or negative association whereas $|P_{x_1x_2}| = 0.$ implies the absence of linear association. Two form parameters x_1 and x_2 having a simple correlation coefficient $P_{x_1x_2}$ with $P_{x_1x_2} \geqslant 0.5$ may be deemed significantly correlated.

Table 2 presents the correlation between hull form parameters.

TABLE 2. HULL FORM PARAMETERS CORRELATIONS [30]

	S	L_{WL}/B_X	B_X/T_X	C_P	C_X	Δ	$\overline{FB}/L_{WL}$	i_E	i_R	i_B	f_B	f_A	T_W/B_X	T_t/T_X
S	1.													
L_{WL}/B_X	.34	1.												
B_X/T_X	-.3	-.32	1.											
C_P	-.2	-.03	+.17	1.										
C_X	-.58	-.02	.05	.01	1.									
Δ	-.69	-.79	-.12	.2	.3	1.								
$\overline{FB}/L_{WL}$	-.19	-.32	.05	.3	.05	.36	1.							
i_E	-.32	-.24	.29	.64	.32	.38	.04	1.						
i_R	-.22	-.1	.13	-.05	.23	.07	-.2	.19	1.					
i_B	-.53	-.25	.16	.27	.54	.38	.12	.54	.23	1.				
f_B	-.14	-.2	.01	-.2	.21	.18	-.03	-.09	.3	.06	1.			
f_A	-.26	.32	.003	.5	.12	.5	.69	.33	-.34	.19	-.03	1.		
T_W/B_X	-.2	-.35	-.04	.24	.16	.5	.5	.38	-.33	.38	.09	.12	1.	
T_t/T_X	[illegible]	-.27	-.02	.5	.44	.54	.51	.47	-.11	.51	.05	.84	.64	1

The body of the table contains the correlation coefficients between any two parameters.

As can be seen in Table 2, the highest correlations are indicated for parameter pairs S - C_x, S - Δ, L_{WL}/B_x - Δ, C_p - i_E, f_A - T_t/T_x, f_A - LCB/L_{WL}, and T_w/B_x - T_t/T_x. Most of these parameter pairs are intuitively obvious from figure 7, the definition of each parameter, and physical reasoning. While for three of the parameter pairs S - C_x, C_p - i_E, and f_A - LCB/L_{WL} it is not immediately apparent that a correlation should exist. Increasing C_x increases the wetted surface and the displacement-though the displacement increases at a faster rate than the wetted surface, hence the negative correlation. If one were to plot the section area at each station against the length of the vessel the centroid of the resulting area curve is the longitudinal center of bouyancy. Hence if one were to increase the area at the after perpendicular, f_A, the centroid of the area would move aft and LCB/L_{WL} would increase. As will be discussed later, a large C_p implies full ends whereas a small C_p implies fine ends—hence the relationship between C_p and i_E. Note also the significant correlation between C_p - f_A, and C_p - T_T/T_x.

Although the correlations presented in Table 2 do not represent a global distribution since the data base was only a few hundred models, the correlations nevertheless represent what may be considered good design practice.

The mutual correlation between parameters presents physical constraints or provides a limiting range of values of each parameter for a certain combination of parameters. The guiding

theorem for naval architects is fairness of the hull lines. Violating this theorem would be detrimental to developing an efficient hull form. For example, consider a Taylor Series form. If we specify a large C_p and a small i_E, the result will be hard shoulders at the quarter, the lines will lack fairness, and the power requirement will be more than it otherwise might have been. This brings up the question of why this combination, or any other combination of parameters might lead to an inefficient or efficient hull form. To respond to this adequately one must consider the hydrodynamics that are involved.

3. Ship Hydrodynamics

Neal's work [30], mentioned previously, resulted primarily with the development of correlation coefficients between the fourteen parameters and the resistance coefficient C_{TL}(Table 3). Further, as a result of his analysis he was able to successfully develop regression equations that are a function of speed and the fourteen parameters. These equations permit the reasonably confident prediction of hull resistance mathematically providing the combination of parameters lies within the model data base (Table 4).

Neal's correlation coefficients for ten of the more significant parameters are plotted in figure 8. It is clear from the figure that the magnitude and sign of association of each parameter as well as the relative importance of each is a function of speed. Also the resistance is closely defined by very few parameters at the high speed end and several parameters at the low speed end. Why these relationships exist is not completely understood due to the complex nature of ship hydrodynamics. However, based on experimental experience, the physics of water flow, and intuition some general comments can be made. Also the mutual correlation between parameters will become evident.

Consider first the overall shape of the hull as expressed by the wetted surface coefficient, and the displacement-length ratio. The wetted surface coefficient is one of the primary determining parameters at the extremes of the speed-length ratio range(figure 8). At the low speed end, frictional resistance

TABLE 3.

CORRELATION COEFFICIENTS BETWEEN C_{TL} AND FORM PARAMETERS BY SPEED [30]

$V/\sqrt{L_{WL}}$	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8
S	.492	.39	.24	.20	.249	.155	-.067	-.224	-.288	-.343	-.335
L_{WL}/B_X	.373	.326	.196	.137	.117	-.032	-.253	-.445	-.519	-.54	-.526
B_X/T_X	.302	.275	.277	.289	.293	.22	.067	.005	.002	-.011	-.017
C_P	.448	.604	.758	.767	.641	.362	.115	-.034	-.056	-.055	-.051
C_X	-.326	-.309	-.265	-.261	-.278	-.182	-.057	.036	.077	.106	.096
Δ	-.452	-.348	-.172	-.107	-.115	.031	.298	.495	.565	.596	.579
LCB/L_{WL}	.071	.117	.183	.198	.154	.039	.012	.01	.035	.022	-.009
i_E	.263	.393	.521	.564	.471	.356	.263	.193	.164	.154	.137
i_R	-.159	-.166	-.153	-.129	-.128	-.064	-.018	.063	.08	.116	.126
i_B	-.243	-.124	.021	.083	.052	.055	.128	.186	.214	.238	.229
f_B	-.224	-.304	-.349	-.356	-.362	-.303	-.173	-.026	-.015	.032	.029
f_A	.163	.25	.33	.308	.224	.094	.046	.02	.039	.016	-.015
T_W/B_X	-.007	.05	.107	.085	.003	-.118	-.099	-.053	-.029	-.049	-.082
T_t/B_X	-.005	.104	.219	.211	.134	.064	.07	.082	.104	.106	.086

TABLE 4

RANGE OF MODEL PARAMETERS [52].

PARAMETER	RANGE
L_{WL}/B_X	5.685 - 13.82
B_X/T_X	2.289 - 4.692
C_p	.5265 - .8705
C_x	.6073 - .9551
4	20.52 - 89.62
$\overline{FB}/L_{WL}$	.491 - .6121
i_E	2. - 25.9
i_R	0. - 35.7
i_B	0.6 - 9.6
f_A	0. - .822
f_B	0. - 0.062
T_W/B_X	0. - 1.076
T_t/T_x	0. - .612
Ⓢ	6.559 - 8.969

TABLE 5.
RELATIVE STRENGTH OF CORRELATION

DECREASING STRENGTH OF CORRELATION WITH C_{TL} →

$V/\sqrt{L_{WL}}$	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8
	S	C_P	C_P	C_P	C_P	C_P	Δ	Δ	Δ	Δ	Δ
	Δ	i_E	i_E	i_E	i_E	i_E	i_E	L_{WL}/B_X	L_{WL}/B_X	L_{WL}/B_X	L_{WL}/B_X
	C_P	S	f_B	f_B	f_B	f_B	L_{WL}/B_X	S	S	S	S
	L_{WL}/B_X	Δ	f_A	f_A	B_X/T_X	B_X/T_X	f_B	i_E	i_B	i_B	i_B
	C_X	L_{WL}/B_X	B_X/T_X	B_X/T_X	C_X	C_X	i_B	i_B	i_E	i_E	i_E
	B_X/T_X	C_X	C_X	C_X	S	S	C_P	T_t/T_X	T_t/T_X	i_R	i_R
	i_E	f_B	S	T_t/T_X	f_A	T_w/B_X	T_w/B_X	i_R	i_R	C_X	C_X
	i_B	B_X/T_X	T_t/T_X	S	$\overline{FB}/L_{WL}$	f_A	T_t/T_X	T_w/B_X	C_X	T_t/T_X	T_t/T_X
	f_B	f_A	L_{WL}/B_X	$\overline{FB}/L_{WL}$	T_t/T_X	i_R	S	C_X	C_P	C_P	T_w/B_X
	f_A	i_R	$\overline{FB}/L_{WL}$	L_{WL}/B_X	i_R	T_t/T_X	B_X/T_X	C_P	f_A	T_w/B_X	C_P
	i_R	i_B	Δ	i_R	L_{WL}/B_X	i_B	C_X	f_B	$\overline{FB}/L_{WL}$	f_B	f_B
	$\overline{FB}/L_{WL}$	$\overline{FB}/L_{WL}$	i_R	Δ	Δ	$\overline{FB}/L_{WL}$	f_A	f_A	T_w/B_X	$\overline{FB}/L_{WL}$	B_X/T_X
	T_w/B_X	T_t/T_X	T_w/B_X	T_w/B_X	i_B	L_{WL}/B_X	i_R	$\overline{FB}/L_{WL}$	f_B	f_A	f_A
	T/	T_w/	i	i	T_w/	Λ	$\overline{FB}$/	B_X/	B_X/T	B_X/T	$\overline{FB}$/

TABLE 6.
RANGE OF PARAMETERS BY DISPLACEMENT-LENGTH RATIO FOR MODELS

	Δ=20-29		Δ=30-39		Δ=40-49		Δ=50-59		Δ=60-69		Δ=70-79	
	H	L	H	L	H	L	H	L	H	L	H	L
L_{WL}/B_X	13.82	10.52	11.06	9.891	10.74	7.94	10.19	7.35	9.15	7.314	5.715	5.685
B_X/T_X	4.037	2.462	3.656	2.487	4.672	2.583	3.848	2.289	3.553	2.289	4.692	4.292
C_P	.6262	.5265	.6628	.5335	.8705	.5537	.6797	.5466	.6585	.5314	.6587	.6421
C_X	.8891	.6336	.8940	.6490	.8705	.6358	.9551	.6073	.9551	.6454	.6585	.6291
$\overline{FB}/L_{WL}$	.5236	.4974	.5663	.4961	.6121	.4910	.5436	.4968	.5481	.5005	.5388	.5328
i_E	8.8	5.5	10.9	2.6	25.9	2.	12.9	5.4	12.1	6.9	12.6	12.
i_R	9.9	5.5	13.9	2.5	35.7	0.	24.4	3.2	25.4	4.1	3.7	3.5
i_B	5.4	1.6	8.6	1.4	9.6	0.6	8.7	1.1	9.2	3.0	3.0	2.9
f_B	0.	0.	.027	0	.062	0.	.053	0.	.0354	0.	0.	0.
f_A	.0185	0.	.414	0.	.822	0.	.279	.004	.219	.0081	.249	.166
T_W/B_X	.654	0.	.861	0.	1.076	0.	.844	.182	.771	.146	.795	.789
T_t/T_X	.0933	0.	.368	0.	.612	0.	.382	.0055	.334	.061	.239	.163
Ⓢ	8.969	7.998	8.45	7.4	8.396	7.208	8.215	6.56	7.973	6.858	8.244	7.761
NUMBER OF MODELS	6		35		100		67		19		2	

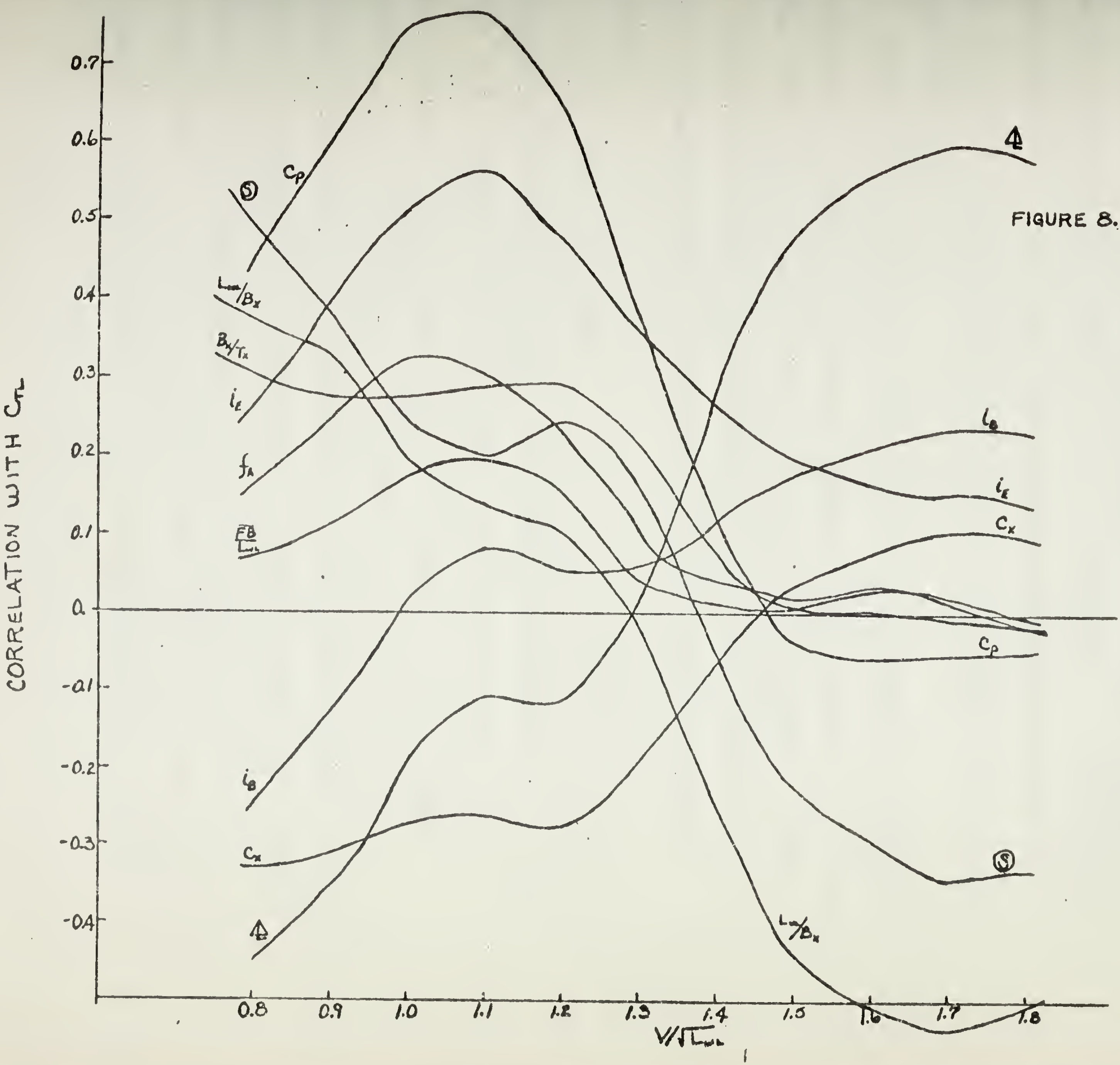


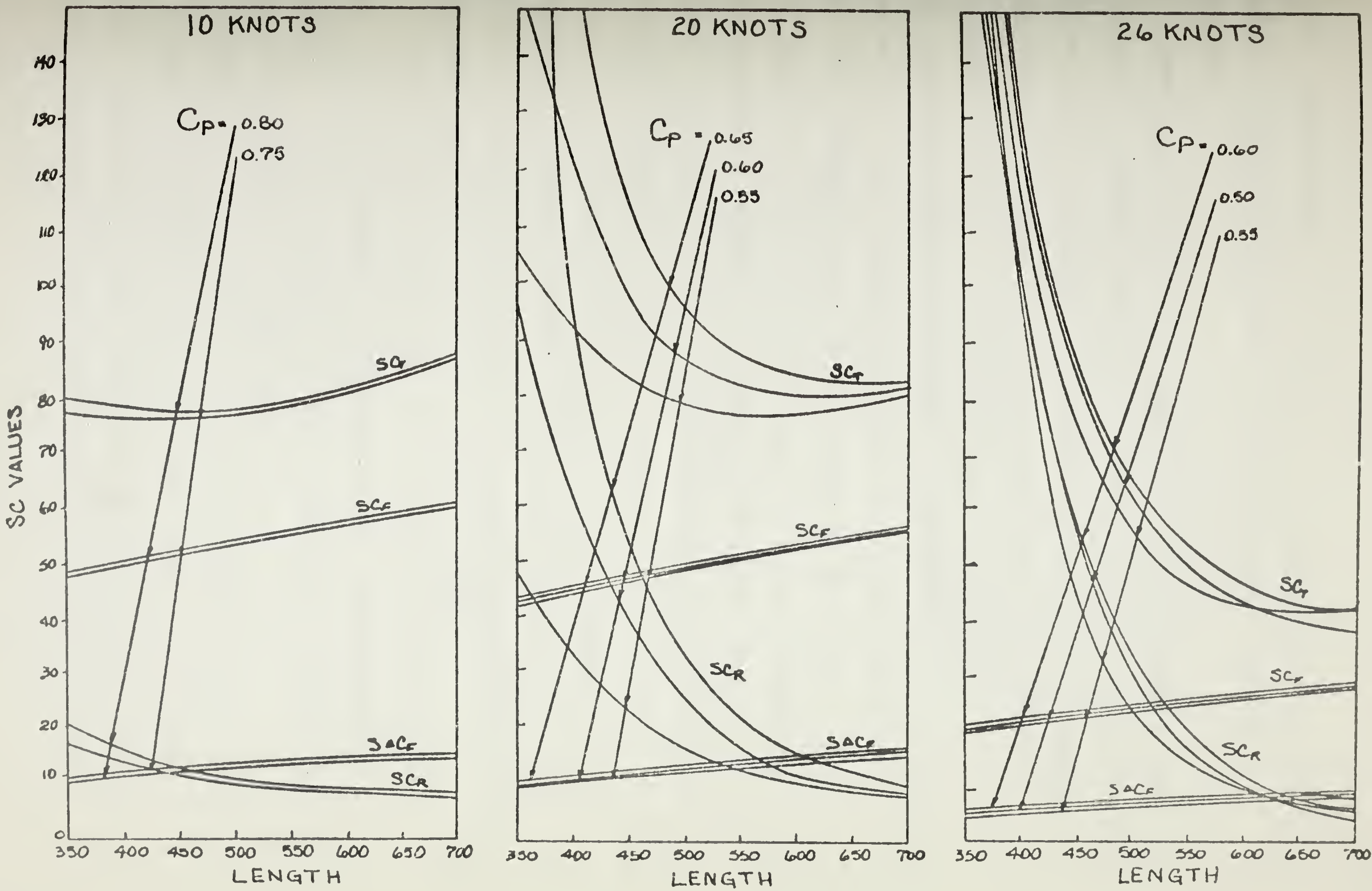
FIGURE 8. CORRELATION BETWEEN HULL PARAMETERS AND C_{TL}

constitutes a large part of the total resistance. Hence it is seen that the greater the wetted surface causing viscous drag, the greater the resistance. This implies firstly that the least ship length possible is desirable. The indication for minimum length is further demonstrated by the negative correlation coefficient of displacement-length ratio(Table 3), indicating large values of $\underline{4}$ yield low resistance. Furthermore, the correlation coefficients for all the other parameters at the low speed end call for values of each parameter that reduce wetted surface.

At the high speed end, the negative correlation coefficient of wetted surface implies that a large wetted surface is desirable. But this is more a result of the greater length needed to minimize residuary resistance(figure 9) than a desire to change other dimensions and coefficients to increase wetted surface.

It is clear from Table 2 that a strong correlation exists between Ⓢ, $\underline{4}$, and L_{WL}/B_x. As already mentioned, at the low speed end a short, full form with a large value of $\underline{4}$, and a small value for L_{WL}/B_x and Ⓢ is indicated. But at higher speeds, since the residuary resistance of the hull greatly exceeds the frictional resistance, and the entire length of the ship is contributing to wavemaking, a slender ship with a small value of $\underline{4}$ and large values of Ⓢ and L_{WL}/B_x is desirable. In other words, at the low speed end the desire for least wetted surface drives the selection of all other parameters, whereas

FIGURE 9. EFFECT OF LENGTH ON RESISTANCE FOR TAYLOR SERIES: 10,000 t, $B_X/T_X = 2$.



at the higher speeds the values for the other parameters which minimize residuary resistance drives the wetted surface to increase.

However, at the extreme high speed end of figure 8 there is a change in curvature of the Δ correlation line. This indicates that an optimum Δ exists. The rate of decrease in residuary resistance is diminishing as Δ is decreased while frictional resistance continues to increase(figure 9). Thus the total resistance goes through a minimum. In reference 5 it is shown that at F_∇ = 1.0 a minimum resistance point will occur at Δ = 24., whereas at F_∇ = 3.5 it occurs at Δ = 17.5.

Figure 10 illustrates the relative effect of different values of Δ on residuary resistance per ton for Taylor Series forms. The change in sign of the mathematically produced correlation coefficient in figure 8 compares remarkably well to the change in the experimentally observed least resistance Δ in figure 10. Although a value for Δ of 28.5 is indicated in figure 10, a practical minimum of 30. must be recognized due to decreasing stability and usable internal volume.

The prismatic coefficient is an indication of pressure drag per unit of weight of displaced water and longitudinal curvature. It is a factor of prime importance in some cases, and quite secondary in others(figure 8).

Figure 11 illustrates the effect of various values of C_p on residuary resistance coefficient for Taylor Series hull forms. Clearly, the lower the value of C_p, the less the residuary resistance for the major portion of the speed range.

FIGURE 10.
EFFECT OF DISPLACEMENT-LENGTH RATIO
ON RESIDUARY RESISTANCE PER TON [10].

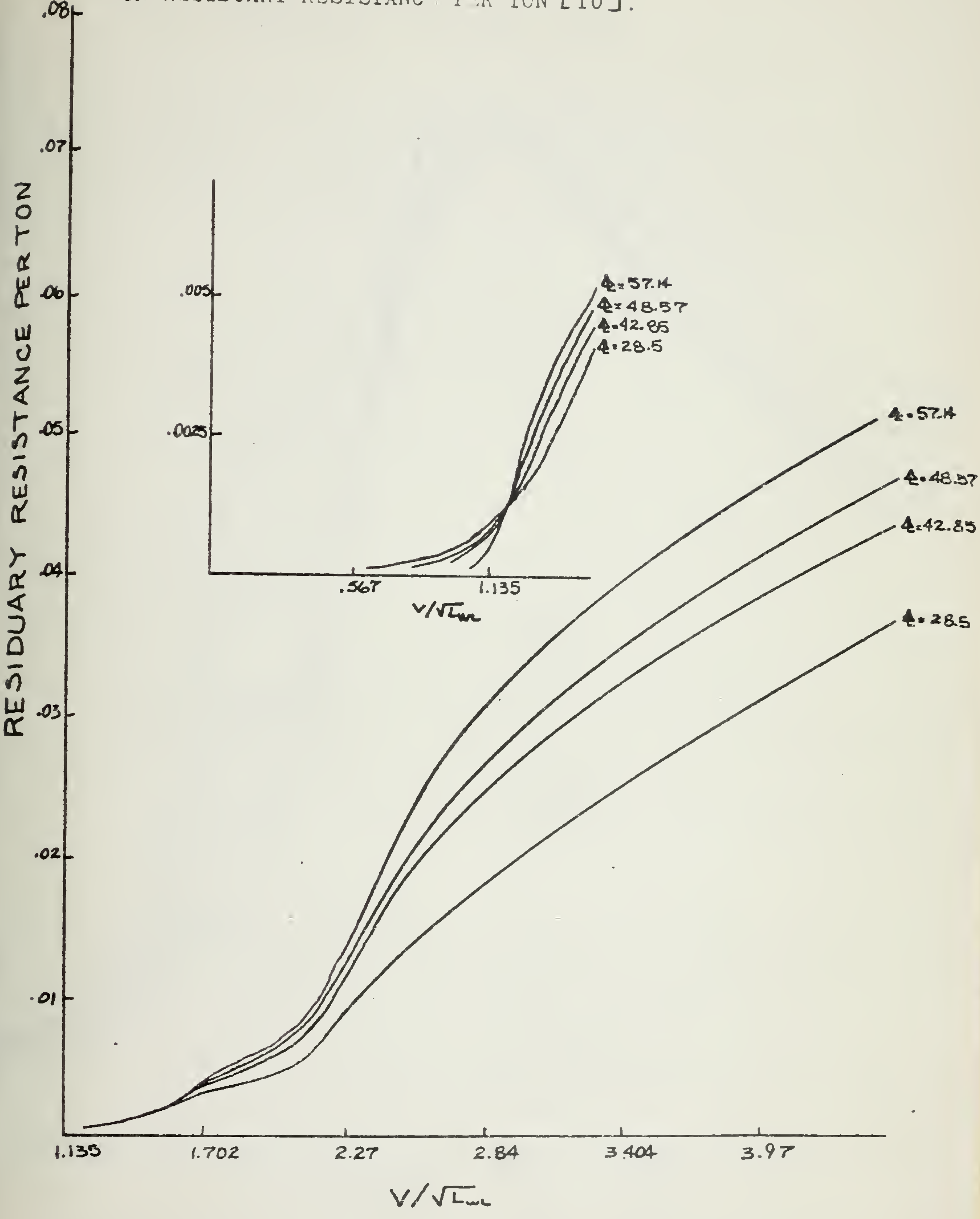
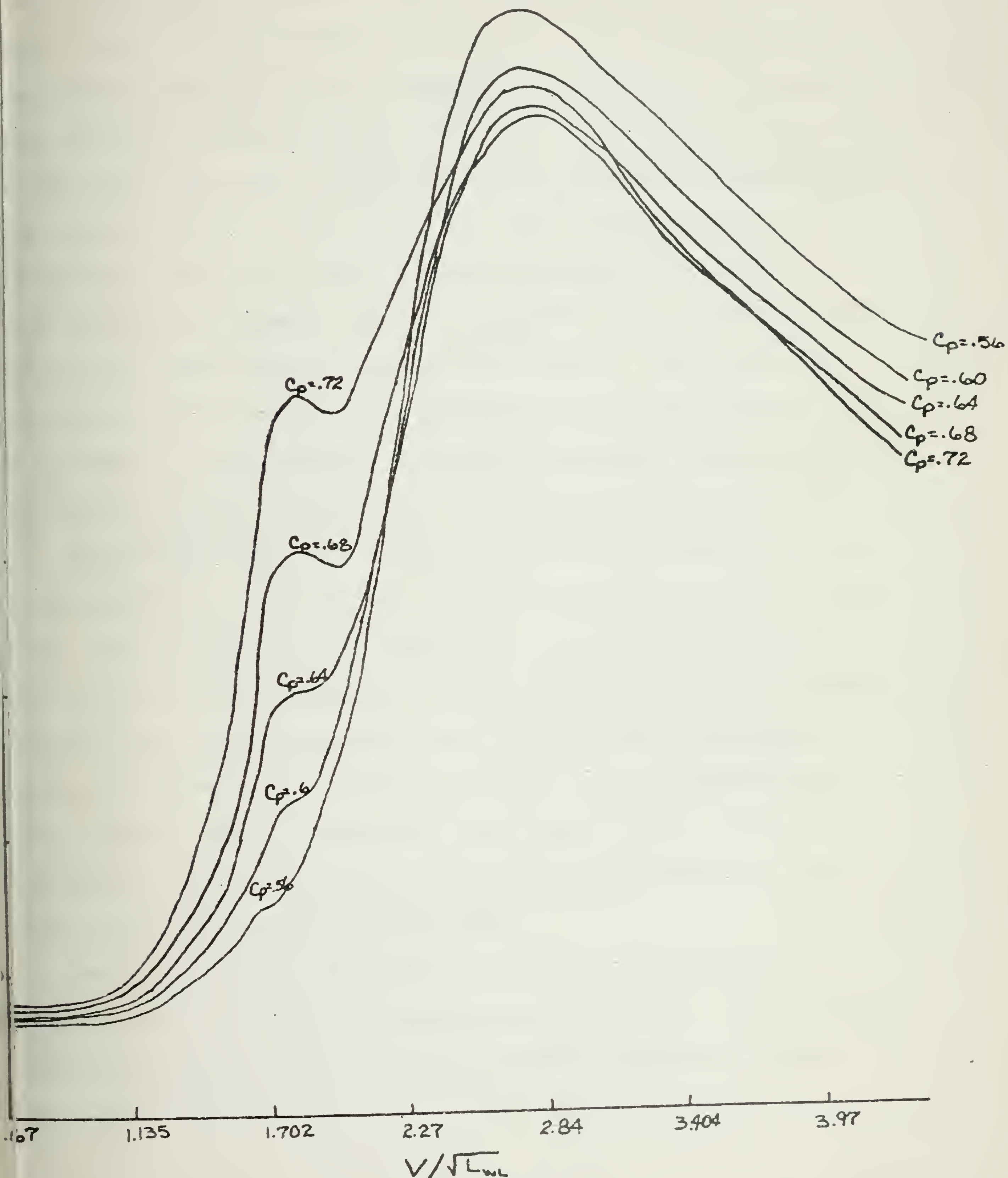


FIGURE 11.
EFFECT OF PRISMATIC COEFFICIENT
ON RESIDUARY RESISTANCE [10].



These results can be explained qualitatively. A small C_p means large area of midship section and full ends. A large C_p means small midship section and full ends. At moderate speeds the ends do the bulk of the wavemaking and the fine ends make much less wave distrubance than the full ends. But at high speeds, the whole body of the ship takes part in the wavemaking, and the smaller the midship section, the less the wavemaking. It follows, that for a ship of given dimensions, displacement, type of form, and speed, there is an optimum C_p or area of midship section for minimum residuary resistance. This involves a minimum overall degree of longitudinal slope and curvature or at least a combination of slope and curvature better suited to easy flow at the speed-length value under consideration.

It is noted that the reversal in the relationship between C_p and residuary resistance occurs near $V/\sqrt{L_{WL}} = 1.45$ in figure 8 and near $V/\sqrt{L_{WL}} = 2.3$ in figure 11. This apparent discrepancy is due to the differences in the general hull form between transom stern destroyers and Taylor Series forms. The reversal occurs at a lower speed in figure 8 due to the need for broad, flat transom sterns indicating a large value of C_p. That is, the shape of the stern forces a value of C_p. Whereas the converse is true for Taylor Series forms.

The range of C_p values for the models(Table 4) is far greater than the range for existing ships(Table 7). Furthermore, although it is difficult to ascribe limiting practical values, good design practice indicates a lower limit of about 0.55 and an

TABLE 7.

RANGE OF HULL FORM PARAMETERS FOR EXISTING SHIPS

PARAMETER	RANGE
L_{WL}/B_x	9.92 - 7.92
B_x/T_x	3.21 - 2.87
C_P	.636 - .56
C_x	.832 - .747
$\triangle$	65.6 - 43.4
FB/L_{WL}	.521 - .504
i_E	17. - 4.8
i_R	18.6 - 4.5
i_B	8.1 - 3.3
f_B	.057 - 0.
f_A	.123 - 0.
T_W/B_x	.69 - .065
T_t/T_x	.238 - .052
Ⓢ	8.95 - 6.98

upper limit of about 0.65 for destroyers operating at speed-length ratios between 0.8 and 1.8.

The midship section coefficient C_x, follows closely an inverse relationship to C_p. The value of C_x appears more as a result of attempting to achieve a certain C_p relative to the expected residuary resistance of the hull and the desire to provide sufficient usable internal volume. The effect of C_x on residuary resistance is shown in figure 12.

Along the same line, the length beam ratio L_{WL}/B_x, although one of the measures of a ship's turning characteristics, is of interest in an analysis of the residuary resistance of a hull form primarily as it may be related to the prismatic coefficient, displacement-length ratio, or the beam-draft ratio. To be sure, a relatively wide ship has more surface water to push out of the way but this effect appears to be less a direct function of the length-beam ratio than of the beam-draft ratio, and the manner in which the pushing is done.

Considering the beam-draft ratio B_x/T_x, experimental data for Taylor Series forms[9], Series 64 forms[5], and figure 13 show a rather consistent pattern of higher residuary resistance per ton for higher values of beam-draft ratio throughout the speed-length ratio range. This is due to the larger slopes and sharper curvatures involved in the wider waterlines and the greater resulting pressure drag due to wavemaking, despite the greater ease with which the water should pass beneath the hull, when the draft is small relative to the beam. This is because

FIGURE 12.
EFFECT OF MIDSHIP SECTION COEFFICIENT ON RESIDUARY RESISTANCE PER TON FOR TAYLOR SERIES MODELS WITH $C_p = .56$, $B_x/T_x = 2.92$ and $\Delta = 3000$. lbs. [45].

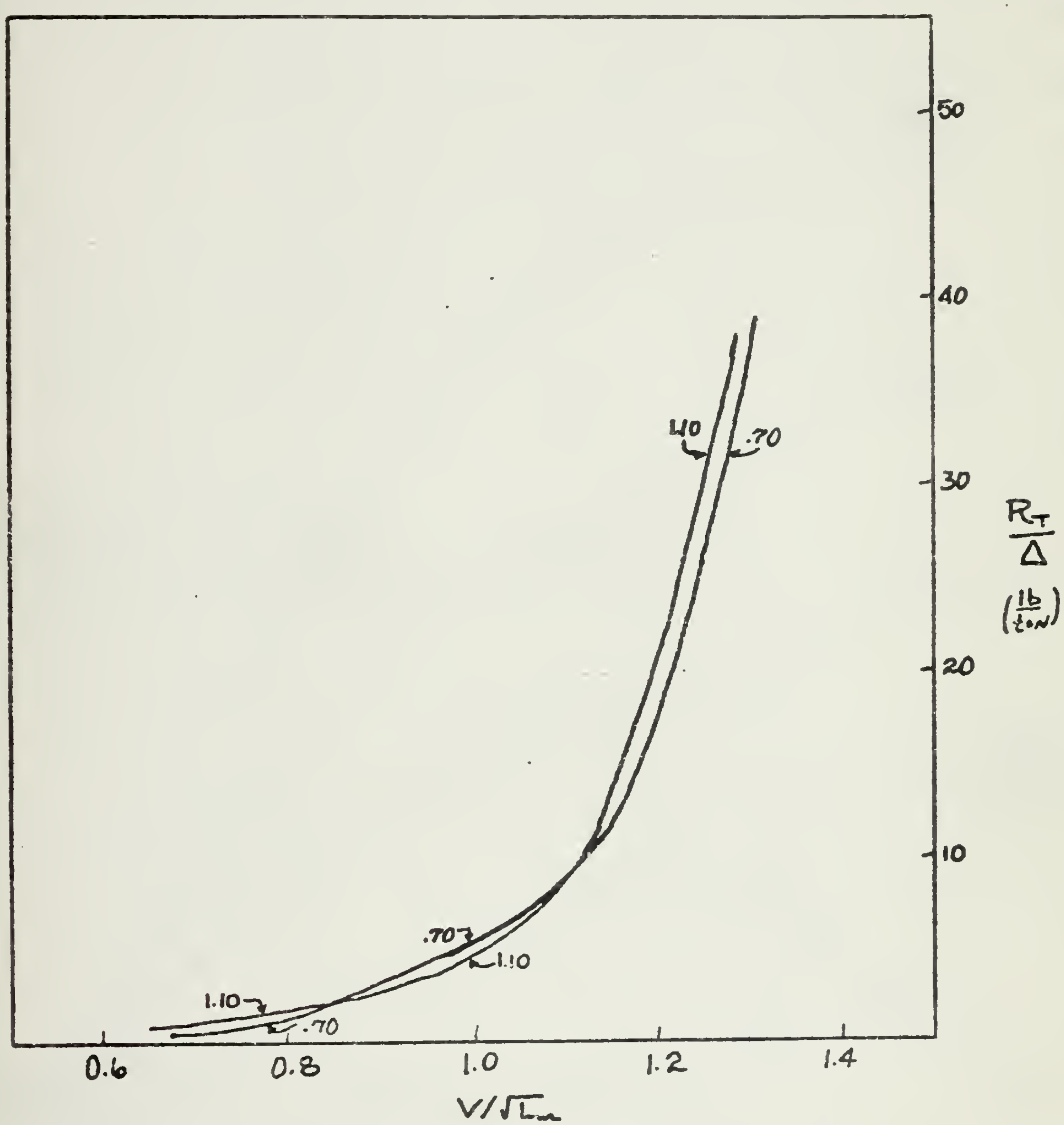
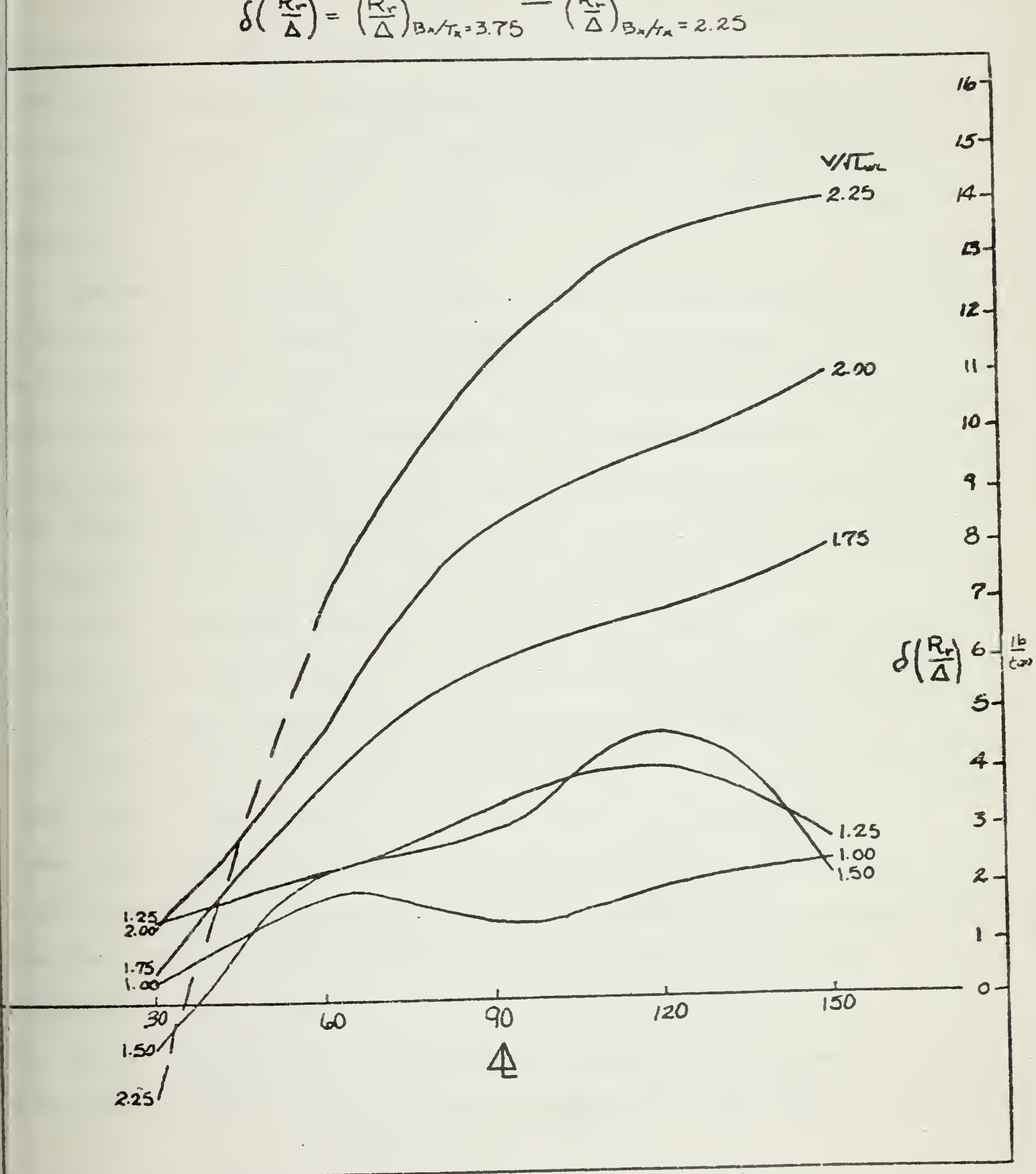


FIGURE 13.
EFFECT OF BEAM-DRAFT RATIO
ON
RESIDUARY RESISTANCE PER TON[54].



wavemaking has been shown to be concentrated at the waterline [6].

It would be desirable then to design with the least value f beam-draft ratio. However beam is one of the governing actors in insuring adequate stability, and draft is limited y depth of harbors, canals, rivers, and dock sills, hence a inimum value of beam-draft ratio is generally necessary on this ccount.

The waterline entrance angle, i_E, has a strong positive orrelation with resistance throughout the speed range. To eflect the incident water at the bow with a uniform transverse cceleration, it would be advantageous to give the entrance aterlines a long, pointed shape, were it not that in practice he length and wetted surface are rather limited. For the design f ships in general, length and wetted surface are major consid-rations as explained before. In addition, a certain amount of aterline area placed well outward from the centerline is needed o give the ship adequate transverse metacentric stability, to ay nothing of useful internal volume and space. The degree to hich a hull form deflects the surface water transversely is herefore a compromise between the advantage of obtaining useful aterplane area on the one hand and the disadvantage of pressure rag due to the deflection of the flow in the entrance and to avemaking on the other.

The entrance angle is particularly important at values of peed-length ratio near 1.1. Also note(figure 8) that the

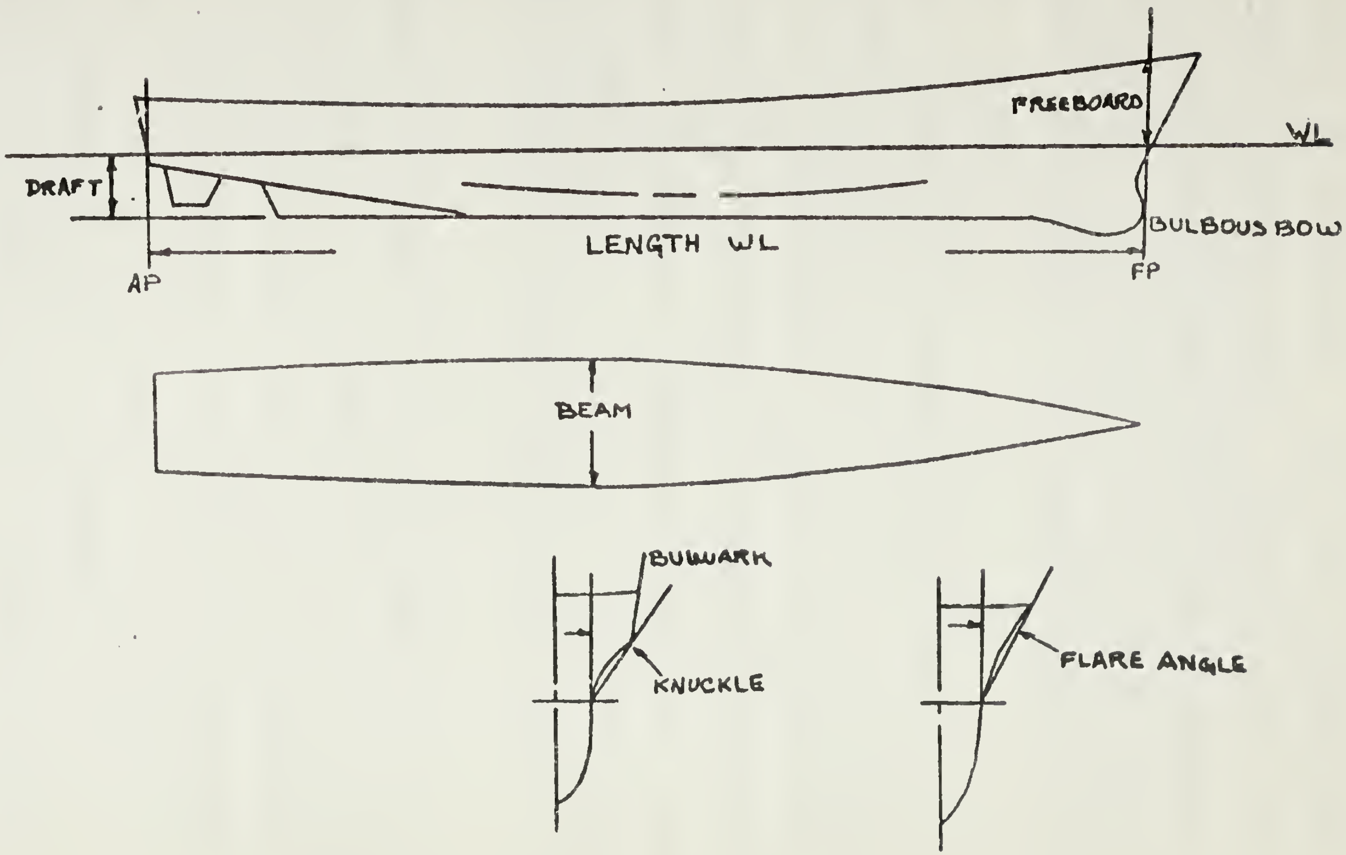
prismatic coefficient and transom stern features are important at this point. It is near this value of speed-length ratio where wavemaking first becomes the dominant part of the total resistance. Only the ends of the ship are contributing to wavemaking and hence the strong correlation. At the higher values of speed-length ratio, as stated earlier the entire length of the ship is contributing to wavemaking resistance, the entrance angle becomes of lesser importance.

Although a considerable range of f_B values is indicated for both models and ships(Tables 4 and 7), the majority of ships have a zero value. However this is quite misleading since a number of ships have a bulbous bow enclosing a sonar, but of such shape and location so that no section area exists forward of the forward perpendicular(figure 14).

Since the wavemaking drag of a ship is proportional to the square of the amplitude of the wave system created by the ship, it follows that any architecture changes which reduce the ship created wave system will result in a reduction in resistance. Properly designed bulbous bows on moderate speed ships, through interference effects, reduce the ship wave system. While on low speed ships they reduce the wave breaking resistance.

The important point regarding bulbous bows is that they are beneficial only at the speed for which they were designed. At other speeds, particularly lower speeds, the bulbous bow increases resistance significantly; the interference effects are not as predominant and form and frictional drag increase. For merchant

FIGURE 14. GENERAL SHIP CHARACTERISTICS [16].



ships which operate at design speed the great majority of their operating time, this is no problem. But naval vessels only infrequently operate at design speed. Figure 15 shows the effect on resistance of a bow mounted sonar for a typical destroyer. Furthermore, bulbous bows are provided on naval vessels primarily due to the improved performance of bow mounted sonars and not for hydrodynamic reasons.

In general if changes in prismatic coefficient are permitted, a greater reduction in resistance will result by decreasing C_p(for $V/\sqrt{L_{WL}} < 1.4$) than by adding a bulbous bow(figure 16).

As mentioned in the discussion of prismatic coefficient and entrance angle, the shape of the ends of the hull is most important around speed-length ratios of 1.1. The after body of the hull is accurately described by f_A, T_W/B_X, T_t/T_X, i_B, and i_R.

The minimization of separation is the prime factor in afterbody design. Reasonably reliable modern data [37] indicates that the slope of a ship's after waterline i_R, at which separation begins, at the air-water interface, is of the order of 13 or 15 degrees. Further, the separation free slope increases at a rate of 0.6 degrees per foot of submergence on a full sized displacement type vessel, up to an estimated critical slope of about 36 degrees at a depth of 40 feet.

A well designed transom stern vessel will have a minimum of separation from the sides of the vessel. A transom stern design recognizes the existence of separation but limits the

FIGURE 15. EFFECT OF BULBOUS BOW ON EHP
FOR A 3000 TON DE.

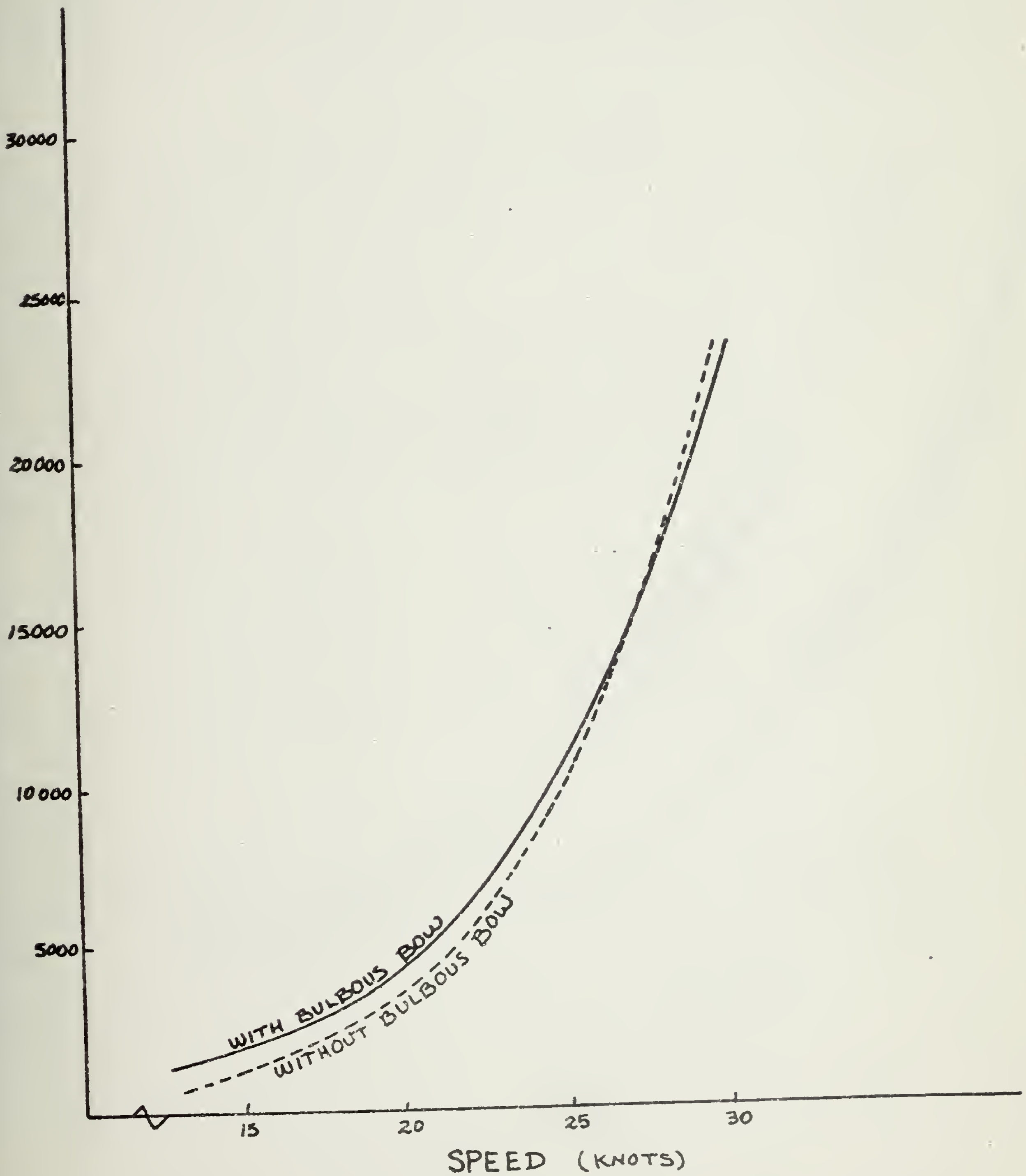
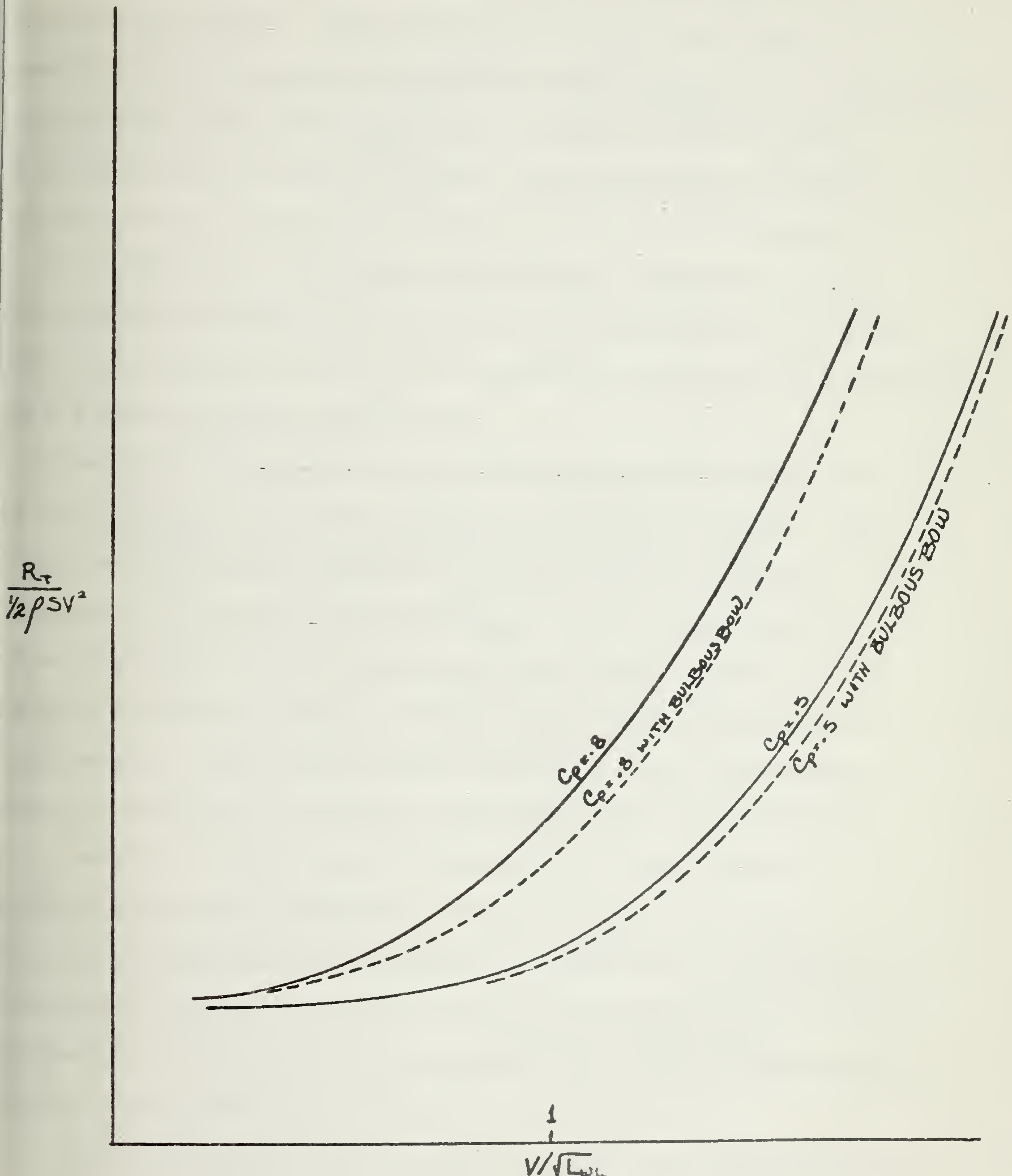


FIGURE 16.
EFFECT OF C_p AND BULBOUS BOWS ON RESISTANCE



separation zone to a definite region abaft the immersed transom; while providing greater deck area and usable internal volume than cruiser sterns. When the vessel is running at low or moderate speed the increased pressure drag caused by the separation is accepted, just as if separation occurred abaft an equal projected area of a cruiser stern. When the ship reaches a certain critical speed the separation zone is ventilated.

As with all of the other parameters, a value for one of the stern parameters which yields a low resistance at a particular speed-length ratio may not necessarily have the same results at a different speed-length ratio.

The buttock angle has a negative correlation coefficient up to $V/\sqrt{L_{WL}} = 0.98$, then changes to a positive value. The negative correlation implies that large buttock angles are desirable. At these speeds($V/\sqrt{L_{WL}} < .98$) the water flowing under the ship fills in easily along the buttock lines, hence separation is not a great problem. The large buttock angles imply rapidly decreasing section areas and hence low wetted surface, reducing the primary resistance component, friction.

However, as the speed of the ship increases, shallow buttock angles are desirable. As more length of the ship becomes involved in wavemaking and the frictional component of resistance becomes secondary, the shallow buttock angles reduce separation drag by providing an easier flow path for the water and hence keep the water attached to the hull.

Similarly, T_W/B_X values should be small and i_R values large

at low values of speed-length ratio to reduce wetted surface. While at the high speeds just the opposite is indicated; to the extreme of having the hull form entirely a forebody. This is to reduce separation at the waterline and improve the effectiveness of the stern in wavemaking.

Low values for f_A and T_t/T_x, as indicated in Table 3, are desired nearly throughout the speed range. Again low values are desired to reduce wetted surface at the low speeds and at the high speeds to allow the water to leave the stern with a nearly horizontal velocity thereby reducing separation and increasing the apparent effective wavemaking length of the vessel, resulting in a reduction of residuary resistance.

Fining the surface and near surface waterlines in the run to reduce or eliminate separation drag in the speed range below which appreciable wavemaking occurs is an operation that pushes the bulk of the ship volume forward. Fortunately it can be accepted there because the blunt entrance does not produce many waves at those low speeds, provided the ship always runs in comparatively calm water. Similarly, fining the entrance waterlines for efficient driving at higher speeds automatically pushes the volume aft. As a result the longitudinal position of the center of bouyancy for least pressure drag, in a vessel of normal shape, shifts from lightly forward of amidships at the lower speed-length ratio values to slightly abaft amidships at the higher values.

The longitudinal center of bouyancy expresses the distrib-

ution of displaced volume. It is a result of deliberate shaping of the hull to produce a desired set of slopes and curvatures in the principle lines of the hull. Its position is therefore to be considered as an effect of the shaping and not as a cause for some desired hydrodynamic performance. There may of course, be practical reasons for locating the LCB at some particular station, such as the necessity for ensuring a certain trim under a specified loading condition, but if good performance is important the proper hydrodynamic design procedure calls for moving the center of gravity to accommodate the LCB and not the other way around.

Thus those values for the hull form parameters that result in a long slender hull of fair lines, with easy curvature will yield a low resistance hull form at high speed-length ratios.

The purpose of the hull is to support and provide a mobile weapons platform for national defense with desirable overall performance features of which calm water speed is but one feature. However there may be a conflict between performance features. As mentioned earlier a fuller hull is frequently chosen to provide the greater usable internal volume demanded by new weapons systems, to the detriment of speed. The question then is to what extent are the other performance features benefitted or penalized by selecting a low resistance hull form.

4.0 Other Performance Features

The other performance features which may be affected by the selection of values for the hull form parameters are the other elements of mobility and the ship's ability to carry weight and provide internal space.

The elements, other than calm water speed, of mobility are:

(1) Endurance - ship range in nautical miles.

(2) Seakeeping - motions and added resistance in a seaway.

(3) Maneuverability - tactical diameter.

A ship's ability to carry weight and provide space will be addressed through weight and volume fractions. The weight of structure, engineering and payload relative to full load displacement will be investigated. Also the usable internal volume and payload volume relative to total enclosed volume will be considered.

It was thought at the beginning of this investigation that relatively simple trends would exist between the primary hull form parameters(Δ, C_p, C_x) and the various weight and volume groups. This has since proved to be rather naïve. The time during which a ship was designed is very important since it reflects the design philosophy and methodology in vogue as well as the state of technology in combat systems, machinery, and ship construction(figure 1). Also the particular mission a ship was designed to fulfill; whether ASW, AAW, or gun fire support has a significant impact. Further, design constraints

override hydrodynamic considerations in some cases. For example, the endurance is frequently constrained to a specific range. The impact of hull form then is how much fuel must be carried. But again this is just as much affected by the power plant efficiency as the hull efficiency. All of these factors have as much if not more influence on space and weight allocation as the shape of the hull.

Nevertheless by recognizing the above factors and utilizing the data available one can discover some trends between hull form and the ability of a ship to provide weight and space for the purpose of carrying payload.

4.1 Weight and Space

4.1.1 Payload

The total payload of a naval ship can be defined as the sum of command and control(weight group 4), outfit and furnishings(weight group 6), crew and effects, armament(weight group 7), and ammunition load. It should be noted that this definition differs from the more widely used definition of payload in that it does not distinguish between military payload and personnel. But in this investigation the allocation of space and weight between military payload and personnel will not be differentiated.

One can see in figure 17, 18, and 19 that the payload weight fraction is a function of time, ship type, displacement, length, and mission. The time trend correlates well with the change from gun ships to missile ships in the late 1950's identified in figure 1 earlier. Figure 18 and 19 show that

FIGURE 17. PAYLOAD WEIGHT FRACTION AS A FUNCTION OF YEAR LAUNCHED

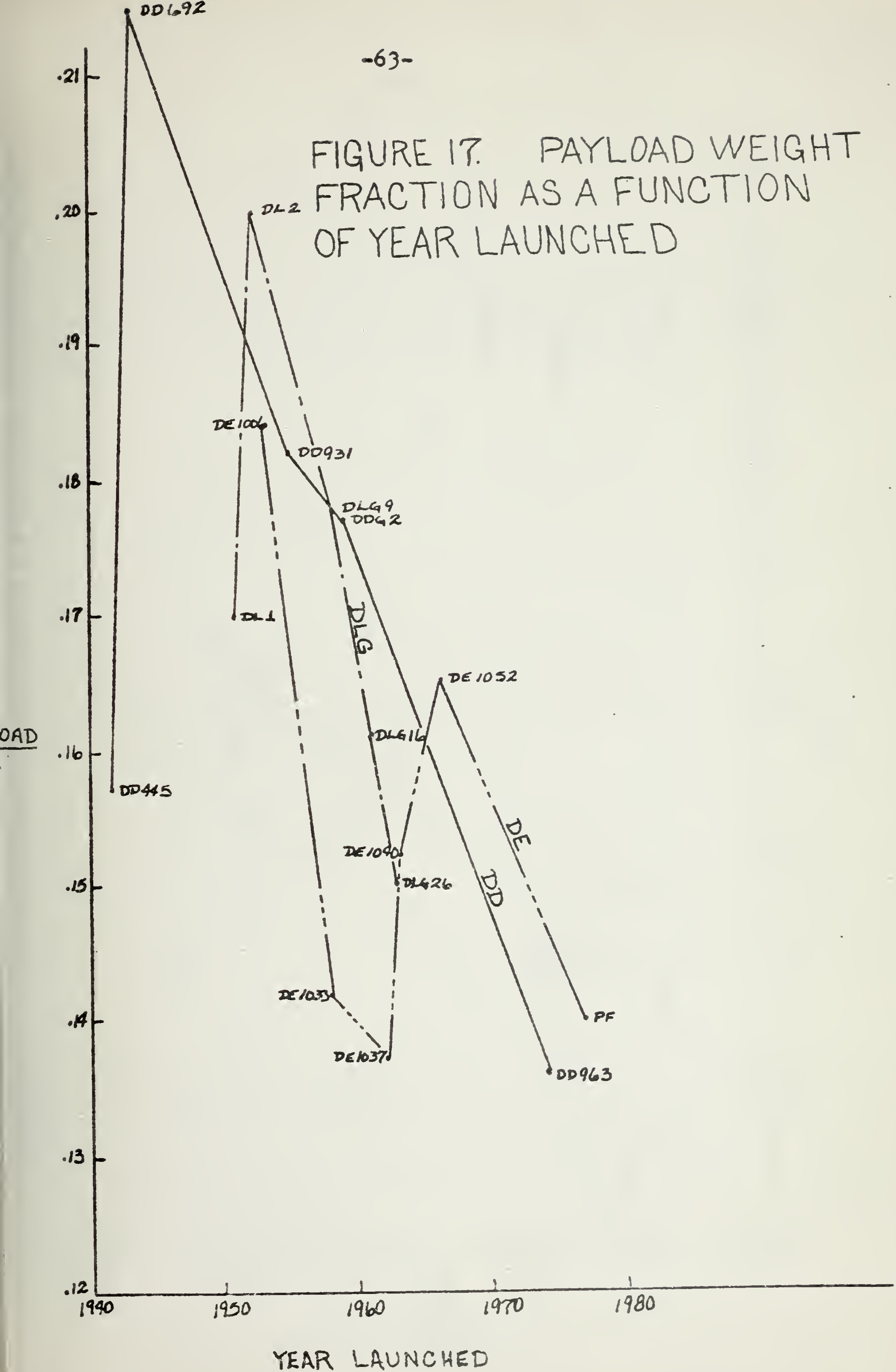


FIGURE 18. PAYLOAD WEIGHT FRACTION AS A FUNCTION OF DISPLACEMENT

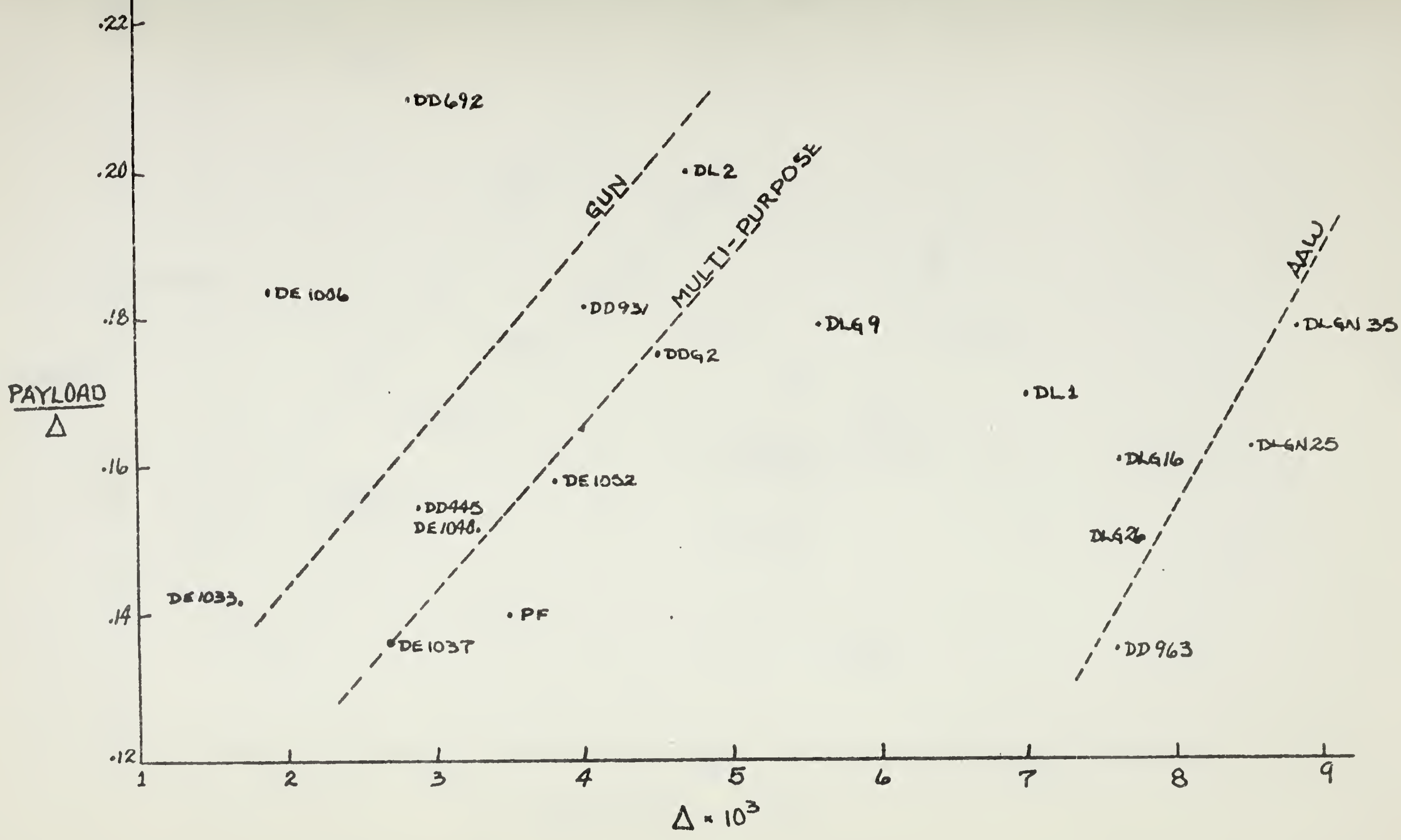


FIGURE 19. PAYLOAD WEIGHT FRACTION AS A FUNCTION OF LENGTH

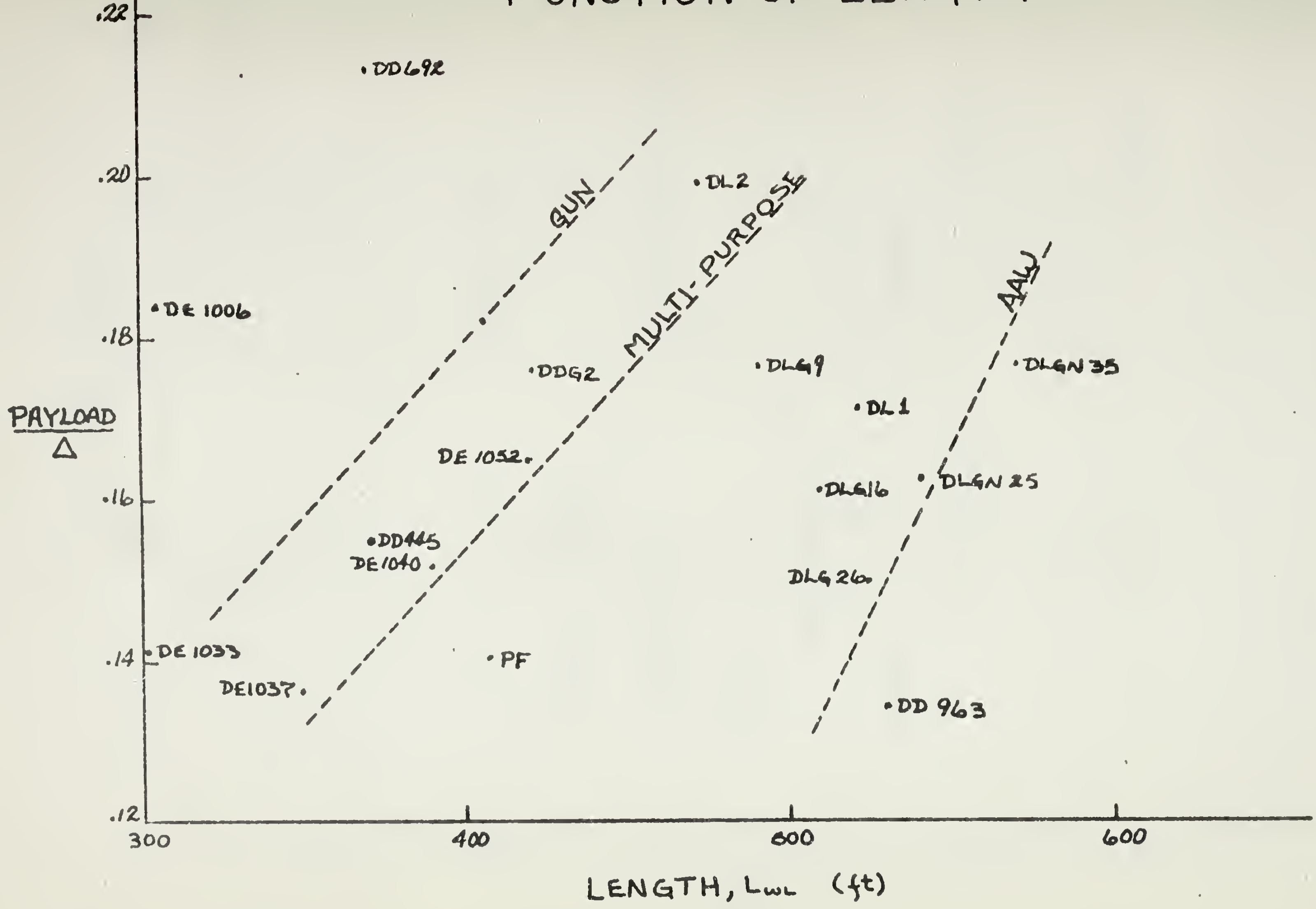


FIGURE 20. NUMBER OF LAUNCHERS VS. LENGTH

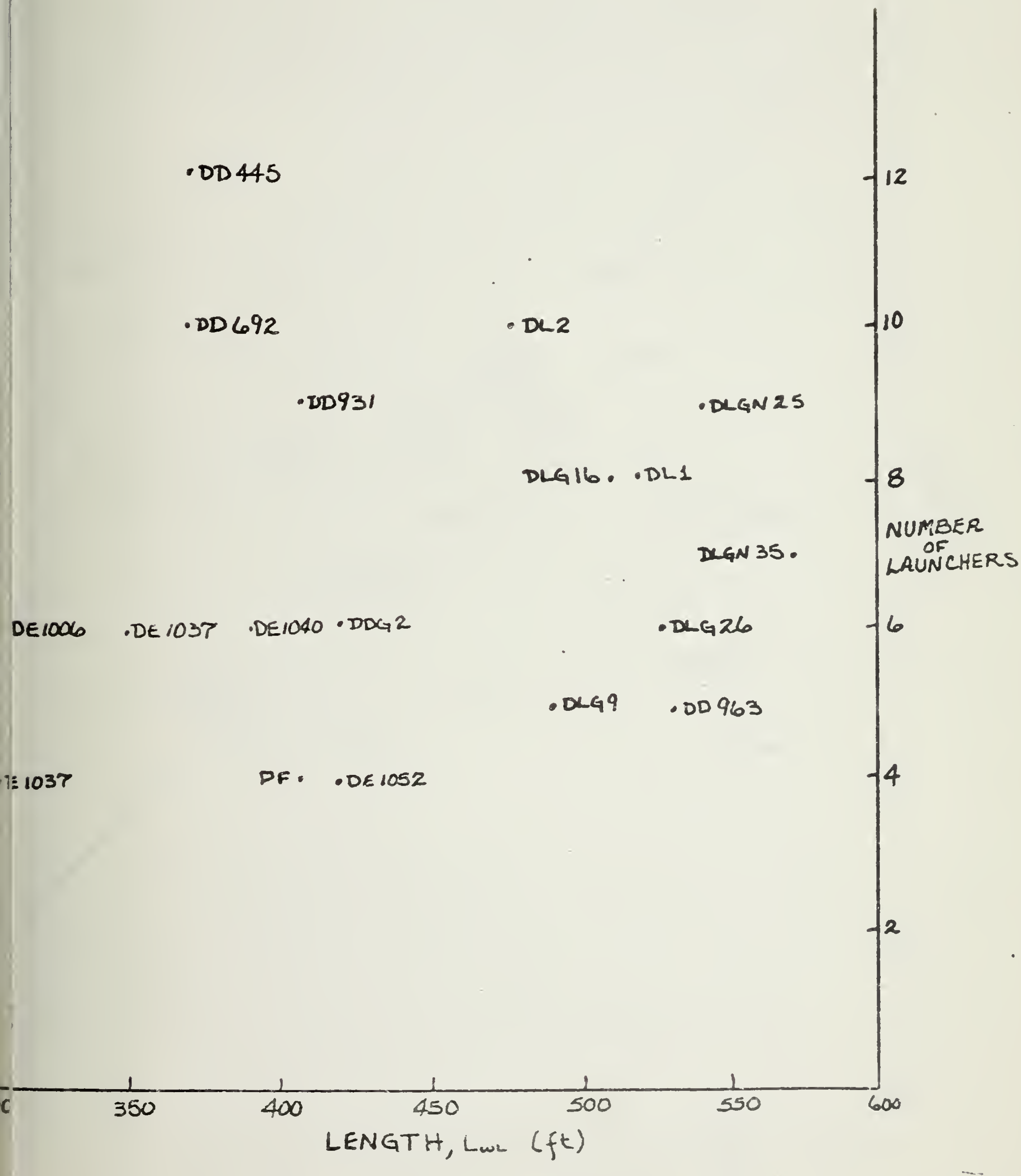


FIGURE 21.
PAYLOAD PER TON VS. DISPLACEMENT-LENGTH

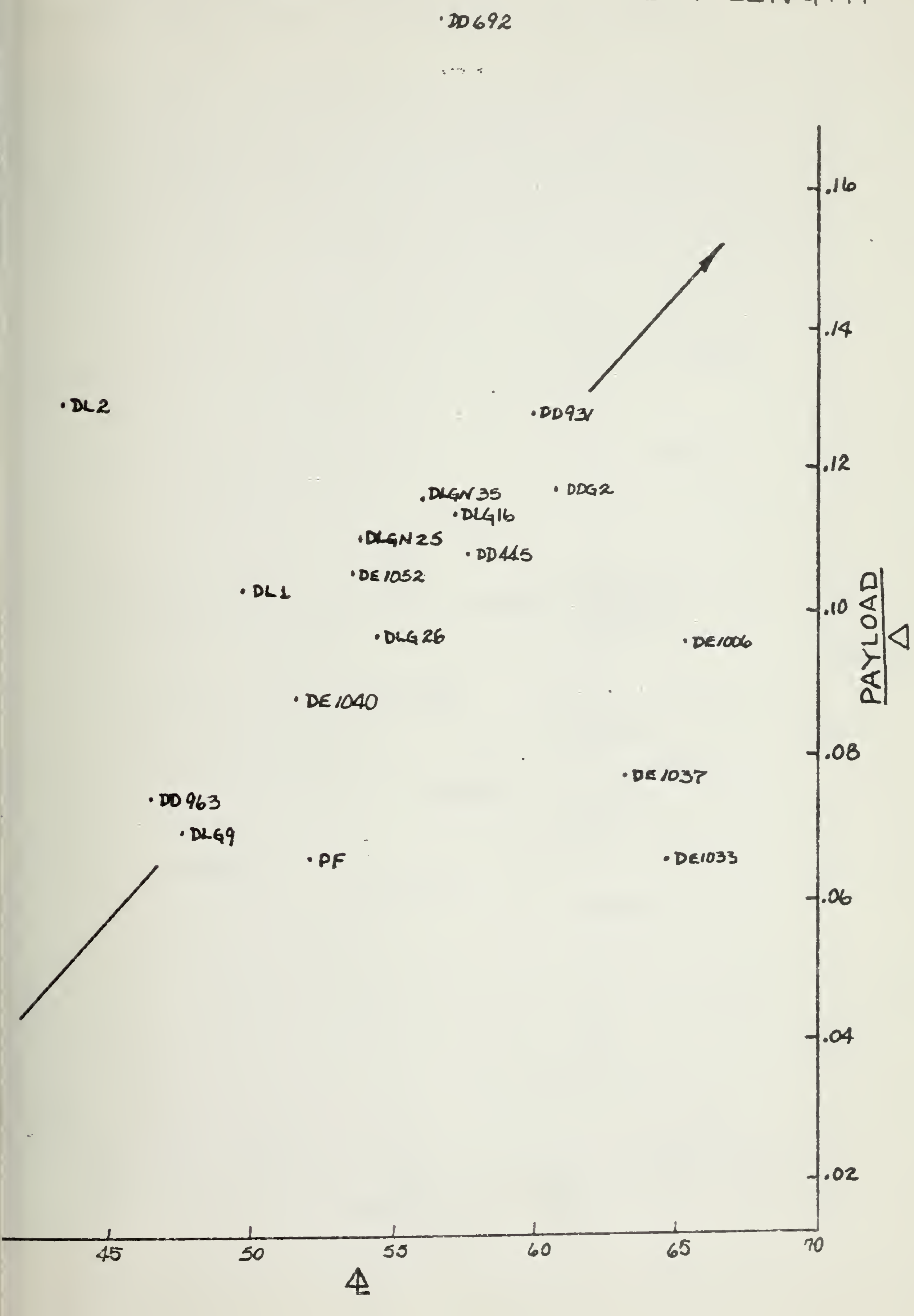
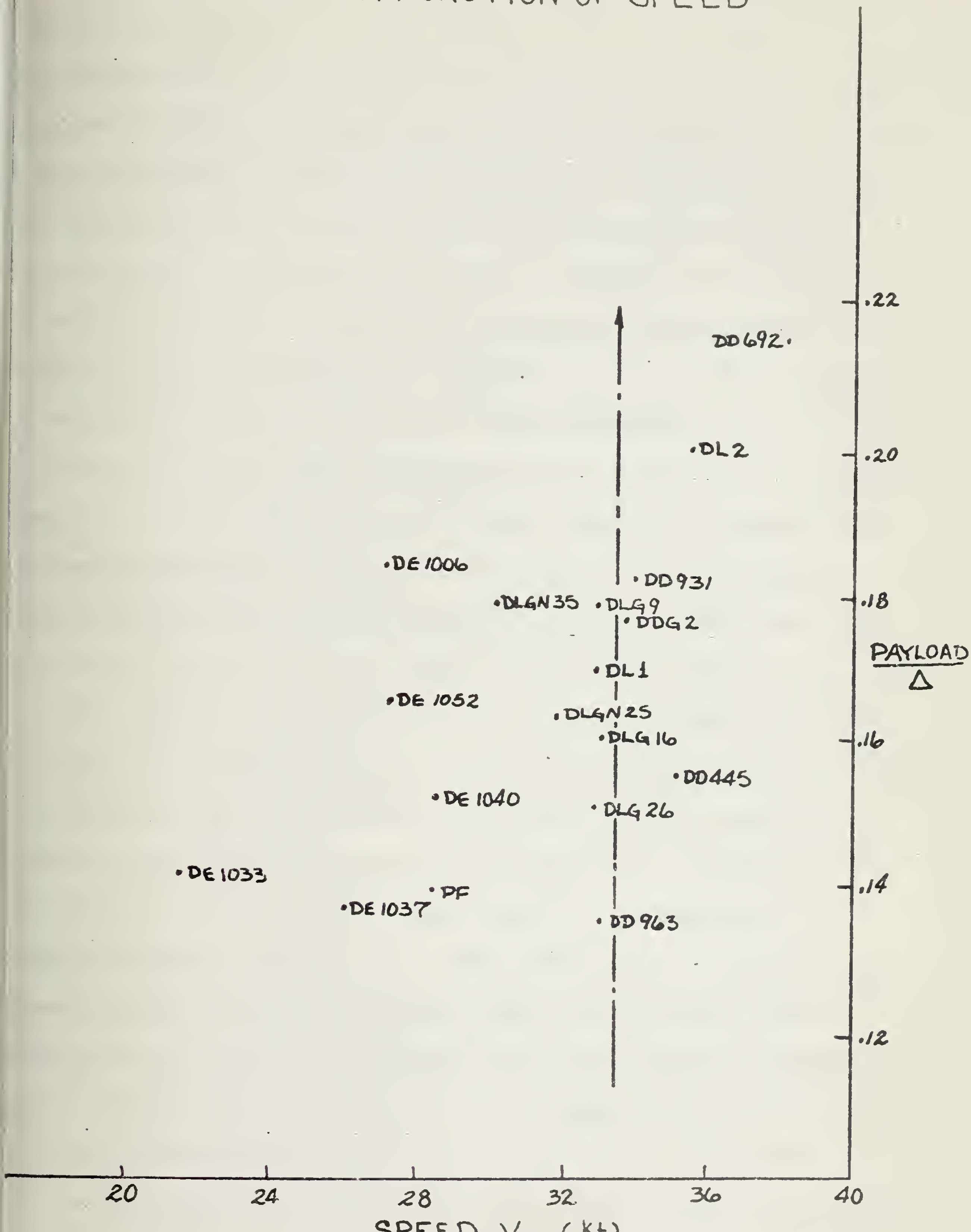


FIGURE 22.

PAYLOAD PER TON AS A FUNCTION OF SPEED



payload weight fraction increases with both ship length and displacement, but is no more dependent on length than it is on displacement. It would seem that the weight fraction should be more dependent on length since a longer vessel would provide a better weapons platform from a weapons arrangement viewpoint. But from figure 20 one can see that the number of launchers is relatively independent of length. Therefore the increase in payload weight fraction for a particular mission with length must be either an increase in command and control, an increase in personnel related weights or larger launchers. The increase in weight fraction with displacement may be due to an increased ammunition load. In any case it is difficult to provide satisfying answers as to the effect of length or displacement independently since neither was held constant while the other was varied, and due to the impact of the other factors mentioned.

The combined effects of displacement and length are shown in figure 21. Payload weight fraction increases with Δ/L. Since low values of Δ/L are strongly associated with low resistance hulls at high speed-length ratios, this figure indicates that the result of designing for high speed is to penalize the payload carrying ability of a ship. That is, an inverse relationship exists between payload weight fraction and speed. Unfortunately figure 22 does not show this clearly perhaps due to the numerous other factors involved. The payload weight fraction varies from 13% to 18% at speeds near 33 knots.

As mentioned earlier, modern naval surface ships are volume

limited. Figure 23 shows that ship density has been decreasing with time. Thus the payload carrying ability of a ship is controlled by usable internal volume. For a given length, if the displacement is increased, greater usable internal volume will be available. This is supported to some extent in figure 24 where one can see that the weight fraction increases with block coefficient, C_B. The greater the block coefficient, the larger amount of volume displaced by a ship in a block defined by the length, beam, and draft.

No observable trends between the other hull form parameters and payload weight fraction was evident. Regretably the volume data available is of such a limited nature that little worthwhile observations can be made.

FIGURE 23.
SHIP DENSITY AS A FUNCTION OF YEAR LAUNCHED

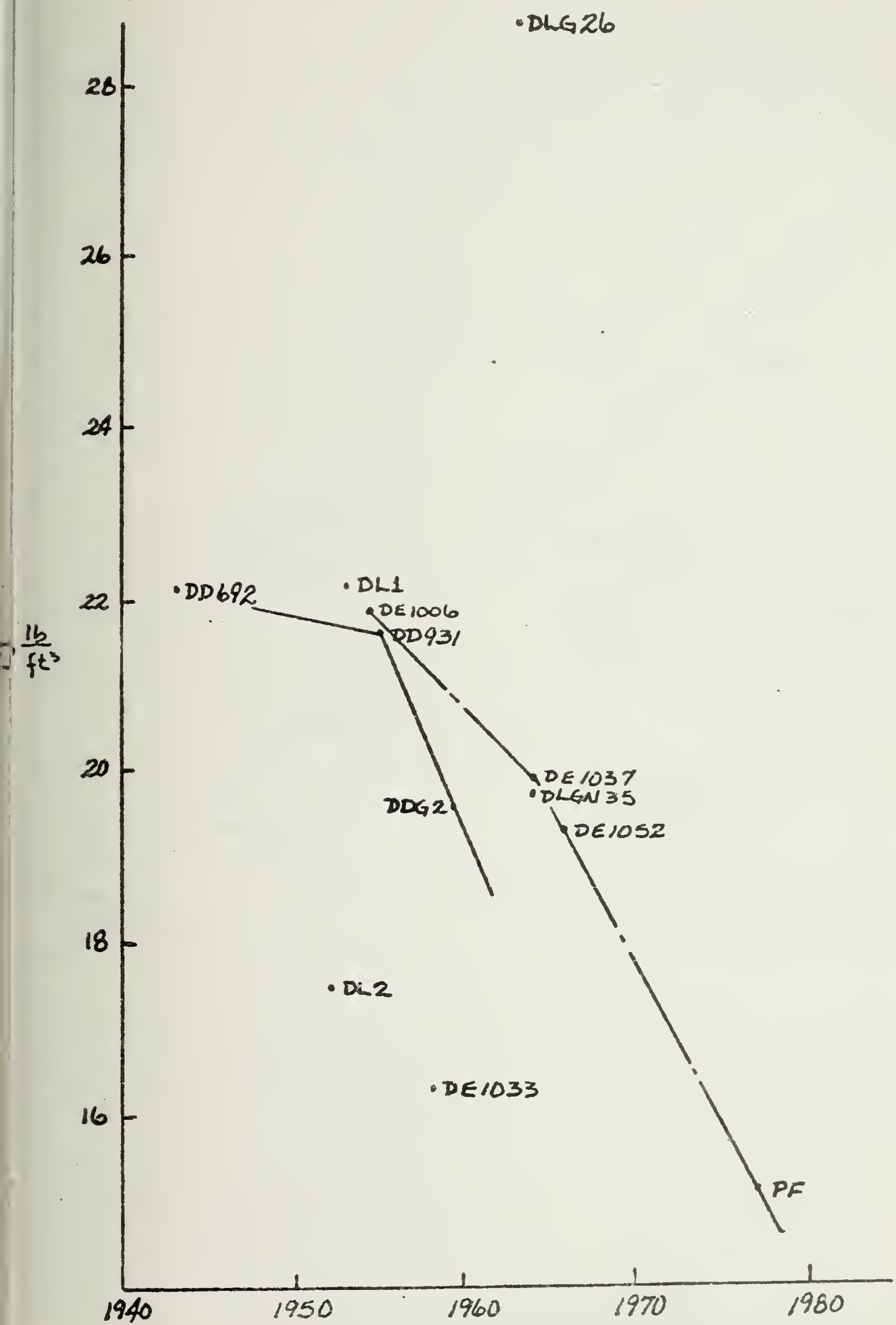
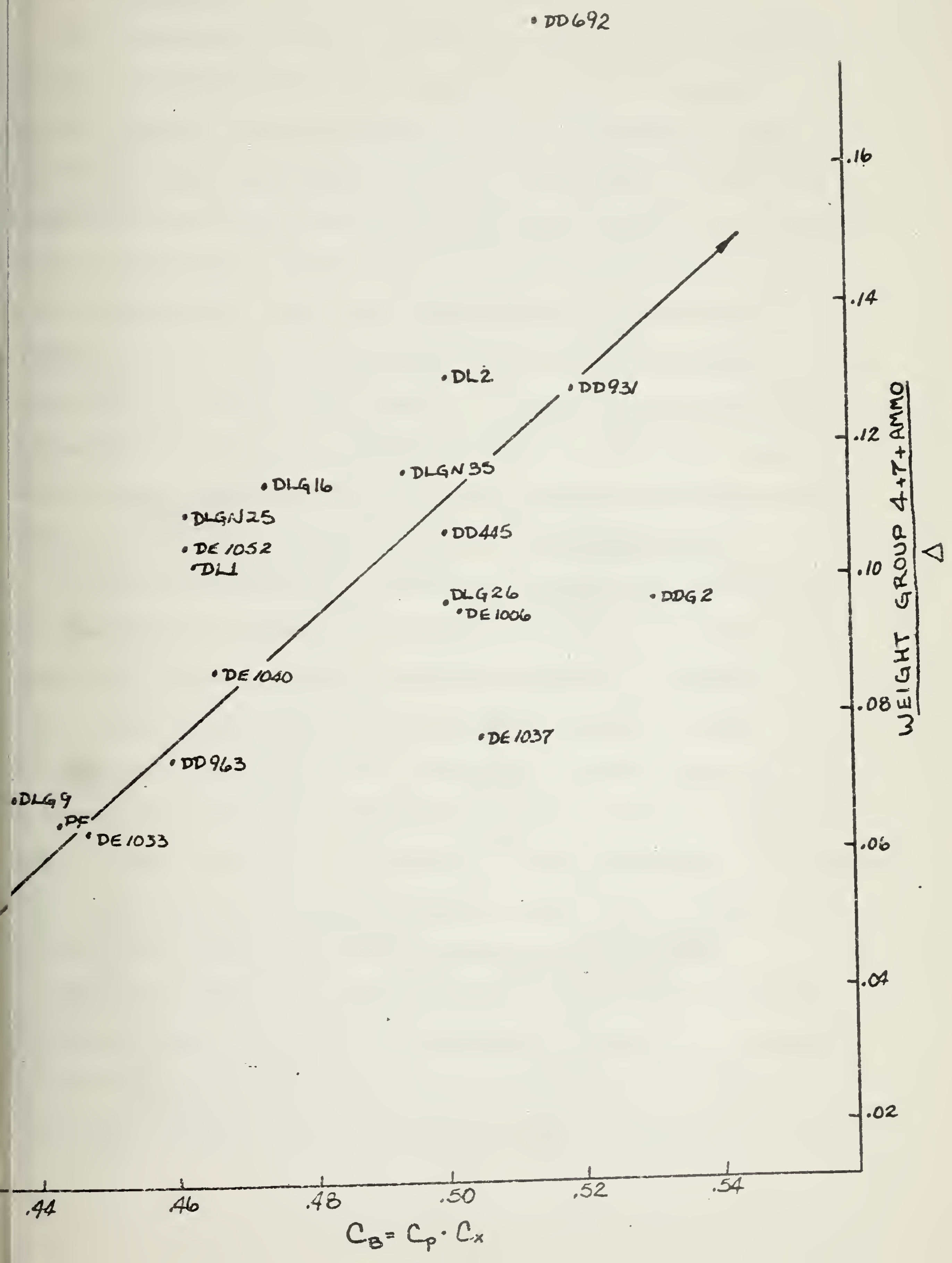


FIGURE 24.

PAYLOAD PER TON VS. BLOCK COEFFICIENT



4.1.2 Structure

The structural weight fraction is also a time dependent element. Improvements in the quality of steel, allowing greater stress in less material, the use of aluminum superstructures, and more highly developed structural design skill should have permitted the structural weight fraction to decrease. However from figure 25 one can see that the weight fraction has not decreased. Why not? The decreasing ship density (figure 23) is a result of devoting more space to people, electronics, missiles, and helos. Also the recent change to gas turbine power plants has had an effect. Thus as a ship carries less weight groups 2, 4, and 7 relative to displacement, the group 1 weight increases relative to displacement.

Other effects are also evident. One can see in figure 26 that length has increased with time. A longer ship will experience a greater level of bending stress in a seaway. Hence, even though the above mentioned improvements have been made the need to ensure that a particular stress level will not be exceeded requires more steel for greater lengths. Figure 27 shows a slight increase in structural weight fraction with length. This is perhaps more clearly shown in figure 28 where one can see that the structural density increases with length.

However these longer ships have also increased displacement and depth. The effect of increasing depth is to increase the stiffness of a ship's structure. The moment of inertia of a section increases and the distance to the neutral axis of the

extreme fiber increases. Changes in the distance to the neutral axis has a greater effect than changing the moment of inertia since the moment of inertia increases only fractionally compared to the linear increase in distance. Thus since,

$\sigma = M_B/SM$

where SM - I/c

and I - moment of inertia

M_B - bending moment

c - distance to the neutral axis

for a given bending moment the stress is increased by increasing depth. Hence more structure is required as indicated in figure 29.

A wave induced bending moment varies as the cube of length [6]. Hence for a given section, increasing length will increase the stress level. Thus the structural weight fraction should increase not only to provide the additional length but to maintain acceptable stress levels (figure 27). A slight increase in weight fraction with displacement is shown in figure 30. The effect of length is present in this figure since the larger displacements were accompanied by greater lengths (figure 31).

The combined effects of displacement and length are illustrated in figures 32 and 33. It can be seen that both the structural weight fraction and structural weight increase with decreasing Δ. Thus designing for high speed performance by choosing a low value of Δ results in a greater structural weight fraction. Consequently payload is penalized.

The only other parameter that showed any degree of correlation with structural weight was the prismatic coefficient. Figure 34 indicates that a generally decreasing structural weight fraction is associated with increasing values of C_p. In the discussion of hydrodynamics it was stated that a small C_p means fine ends and a large C_p means full ends. Therefore if we assume we have two ships of the same length, the ship with the large C_p will have slightly more shell plating and stiffeners but a significantly larger displacement due to the full ends. Hence the decreasing weight fraction is due to the larger displacement associated with the larger C_p.

FIGURE 25.
STRUCTURAL WEIGHT FRACTION VS.
YEAR LAUNCHED

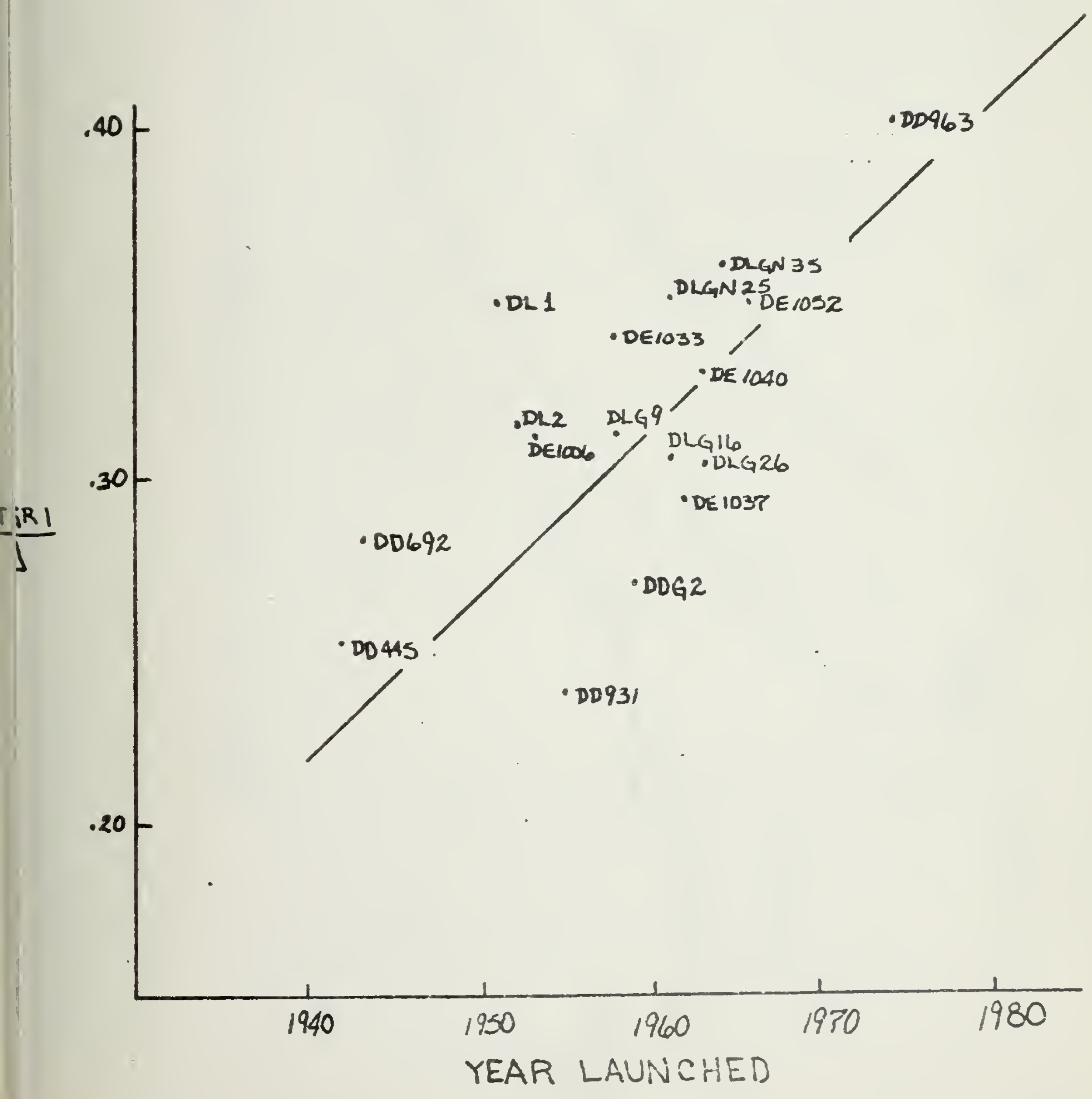


FIGURE 26. LENGTH AS A FUNCTION OF YEAR LAUNCHED

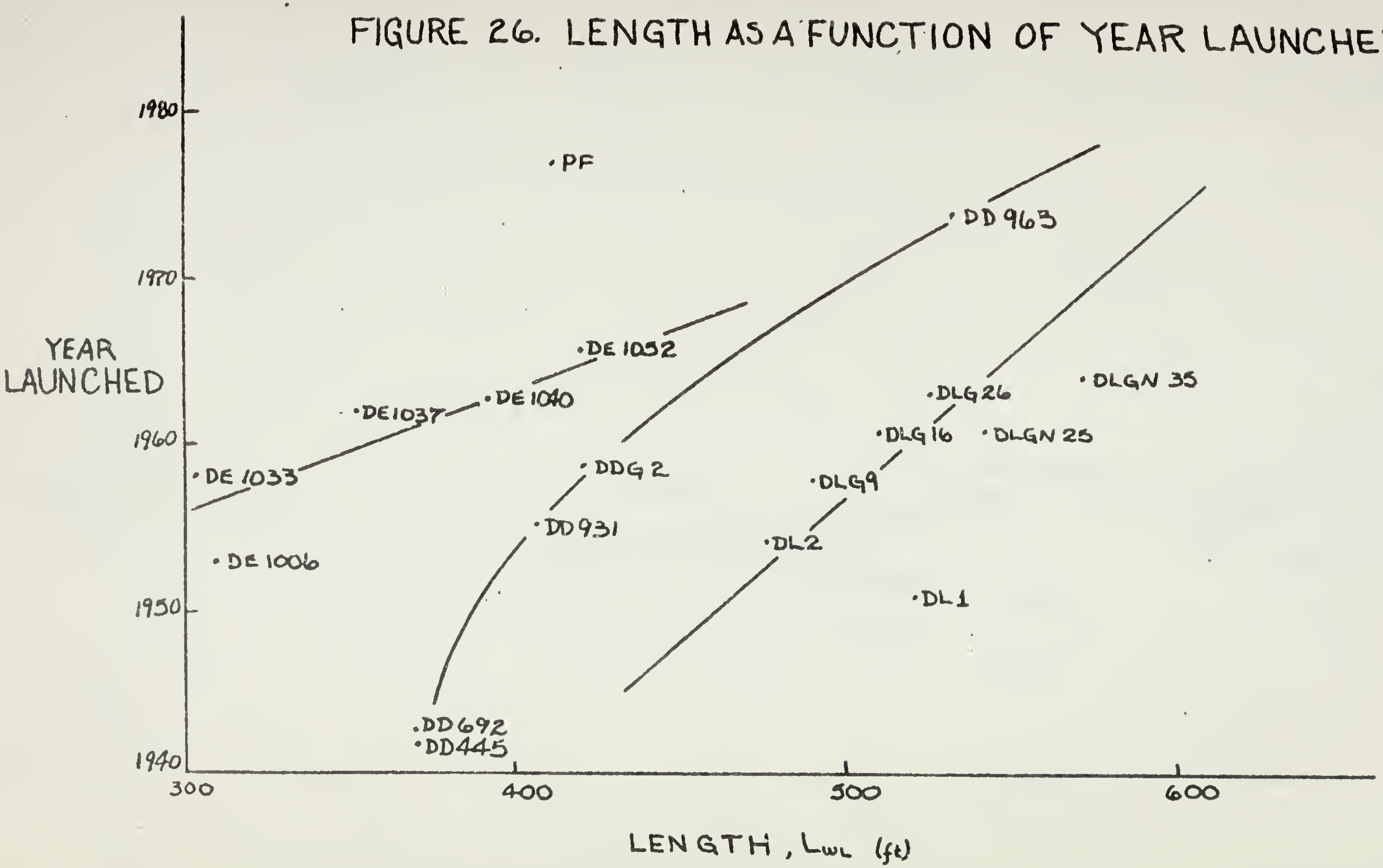


FIGURE 27. STRUCTURAL WEIGHT PERTON VS. LENGTH

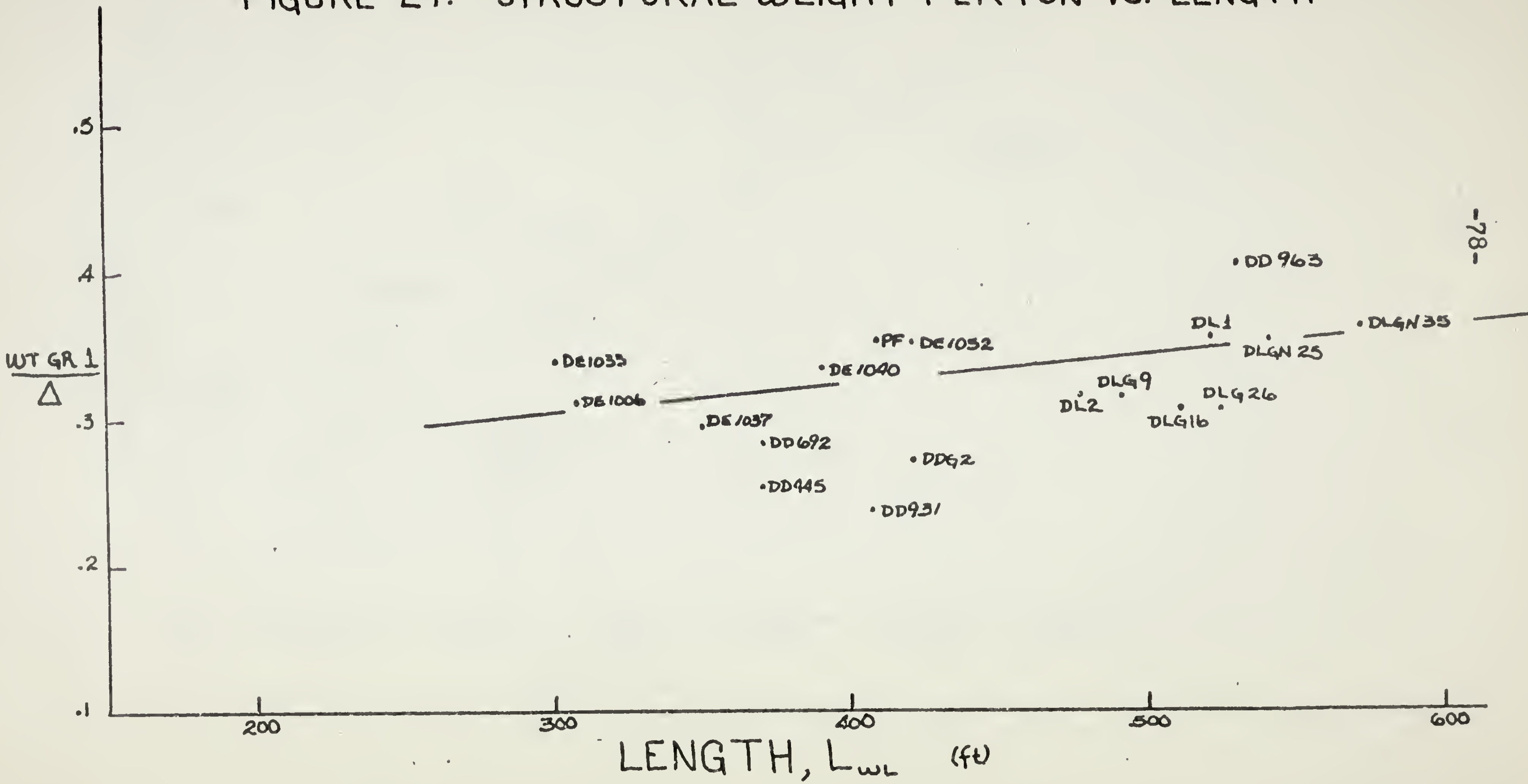


FIGURE 28. STRUCTURAL DENSITY VS. LENGTH

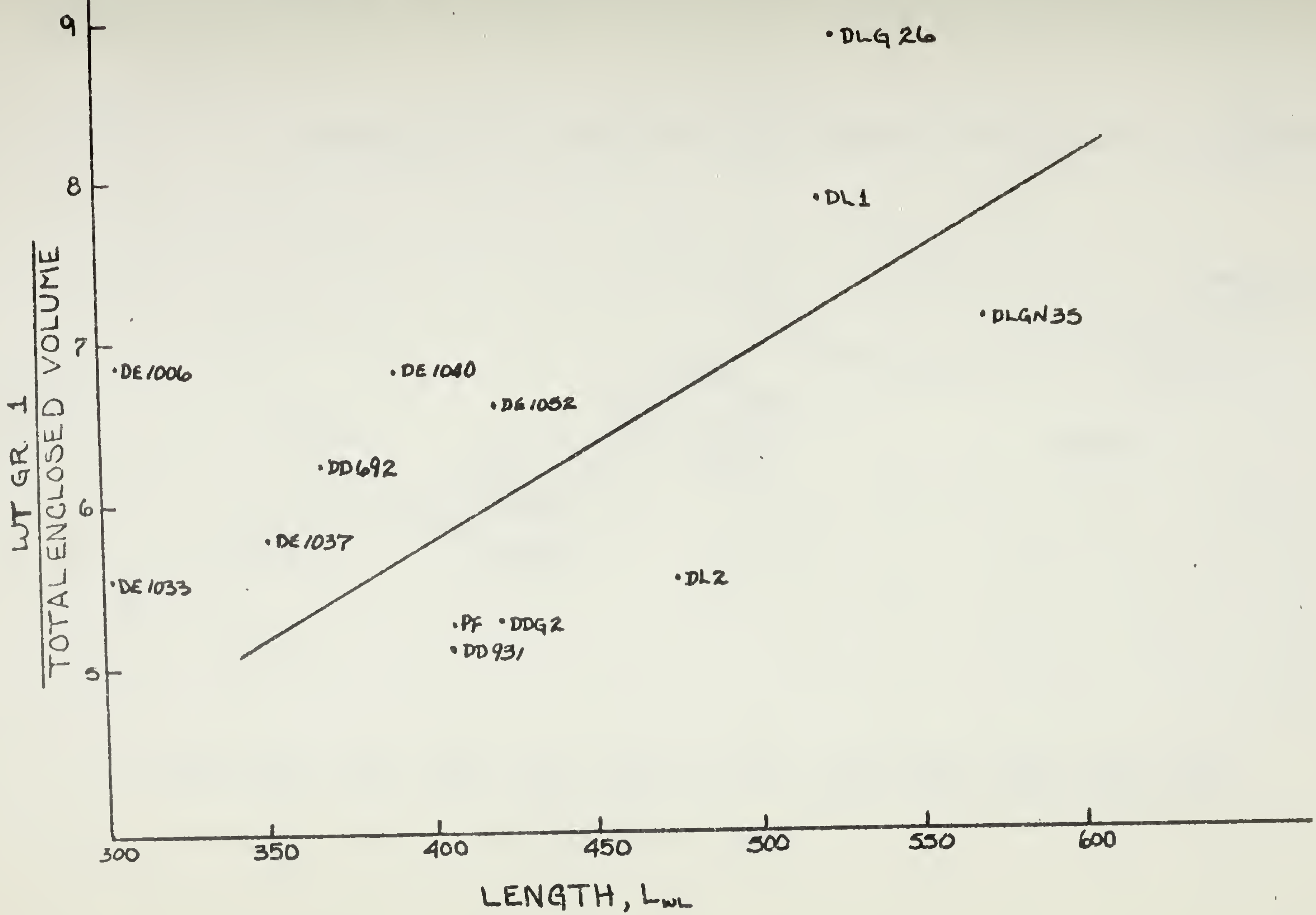
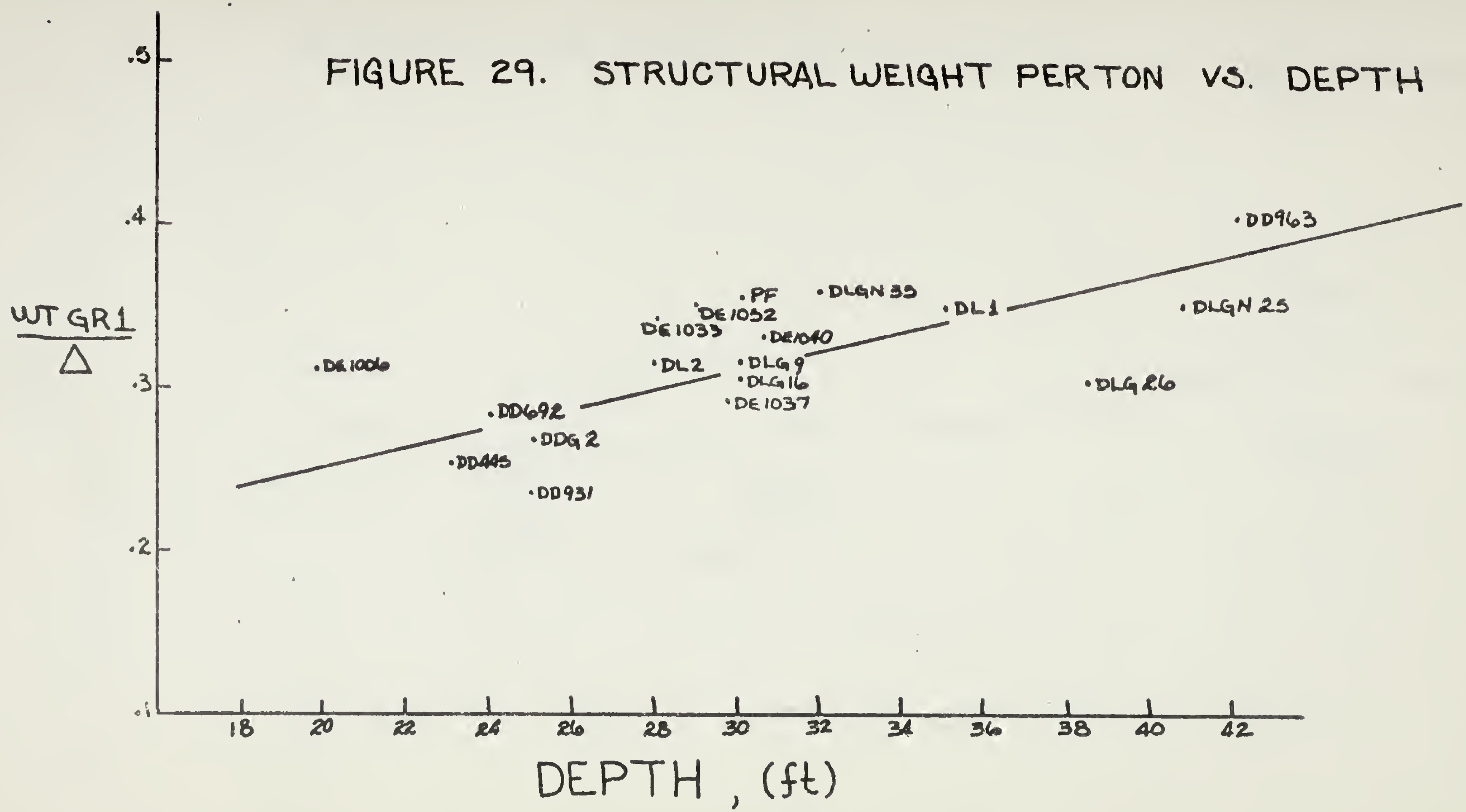


FIGURE 29. STRUCTURAL WEIGHT PER TON VS. DEPTH



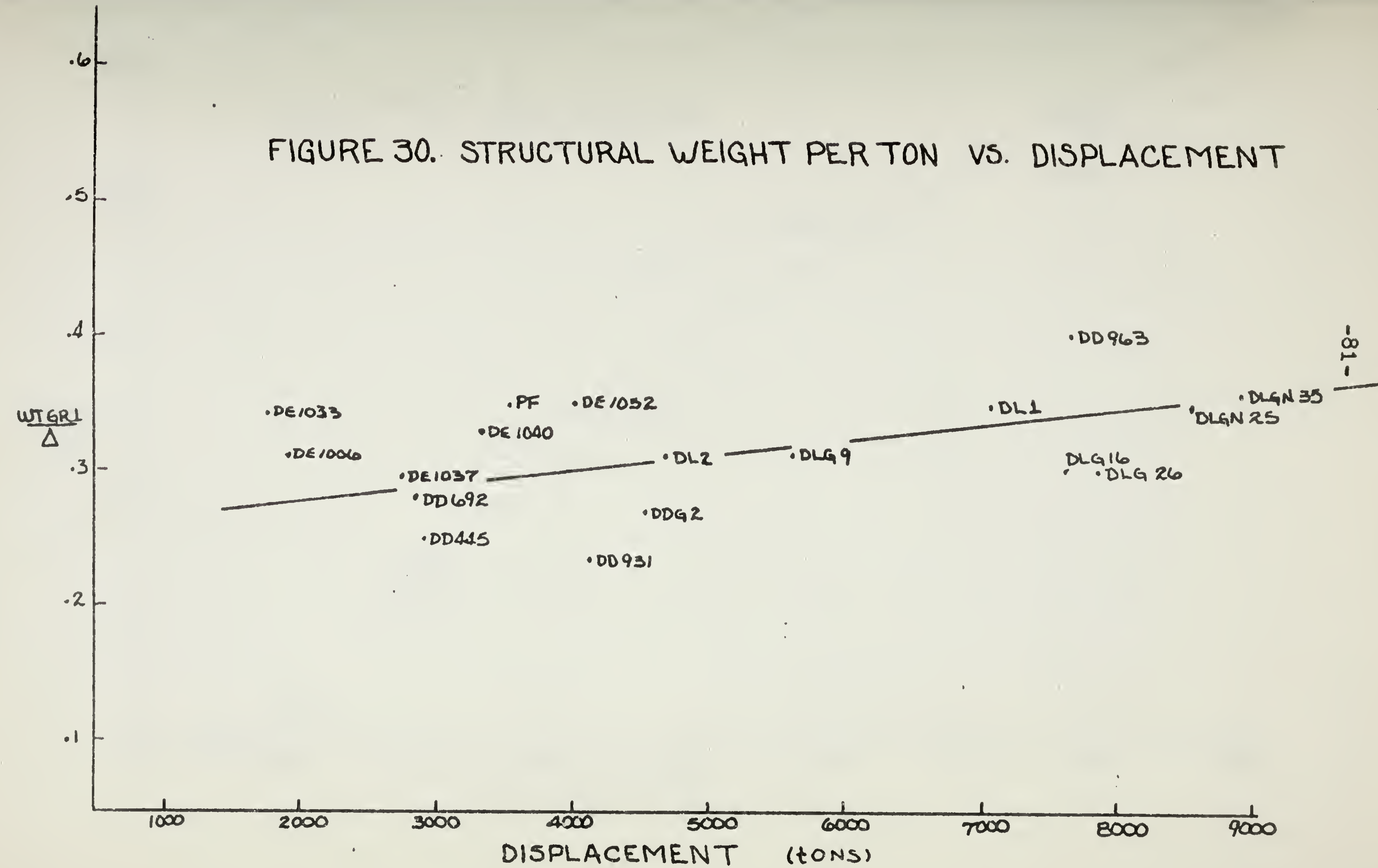


FIGURE 30. STRUCTURAL WEIGHT PER TON VS. DISPLACEMENT

FIGURE 31.
LENGTH VS. DISPLACEMENT

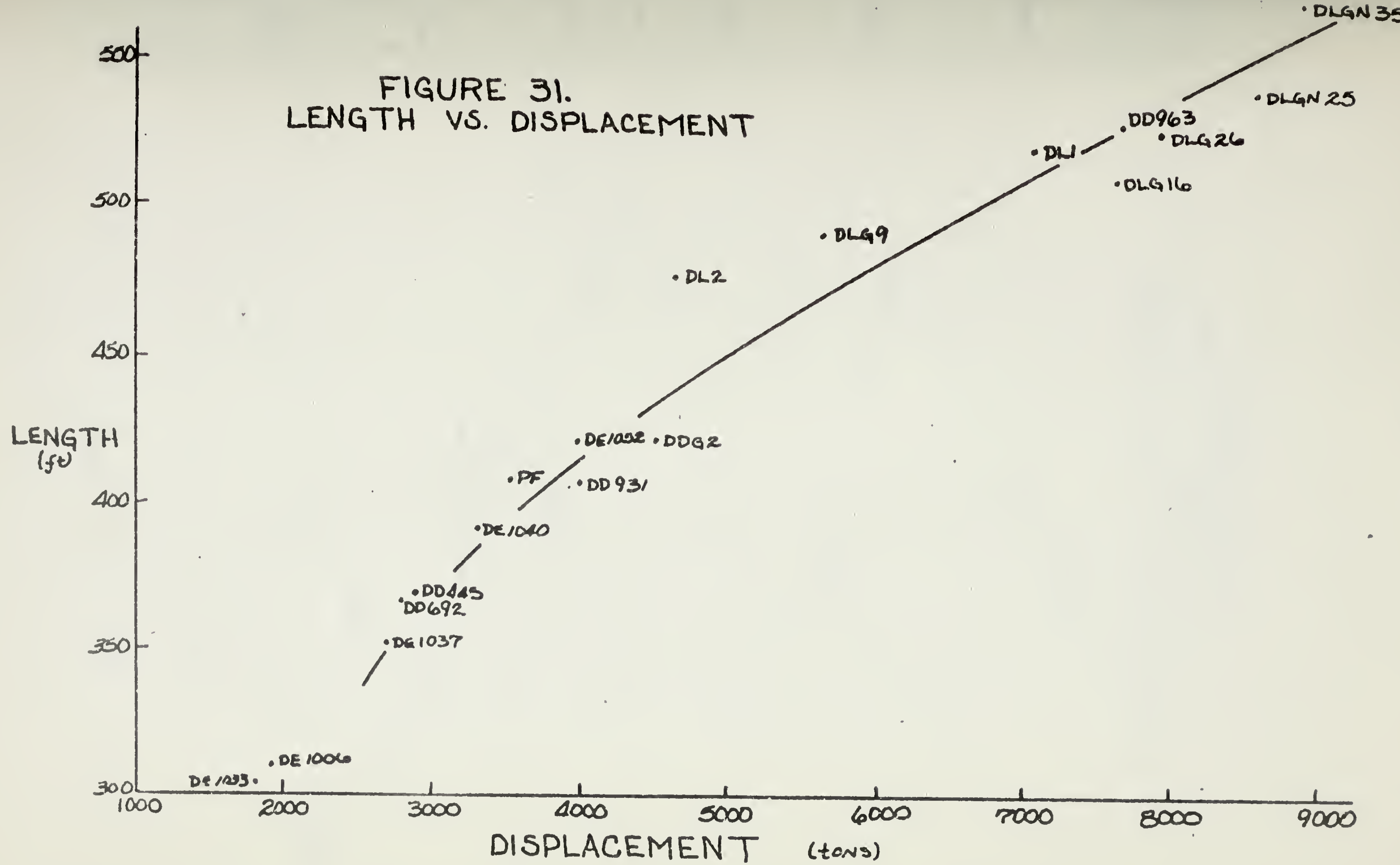


FIGURE 32.
STRUCTURAL WEIGHT
VS.
DISPLACEMENT-LENGTH RATIO

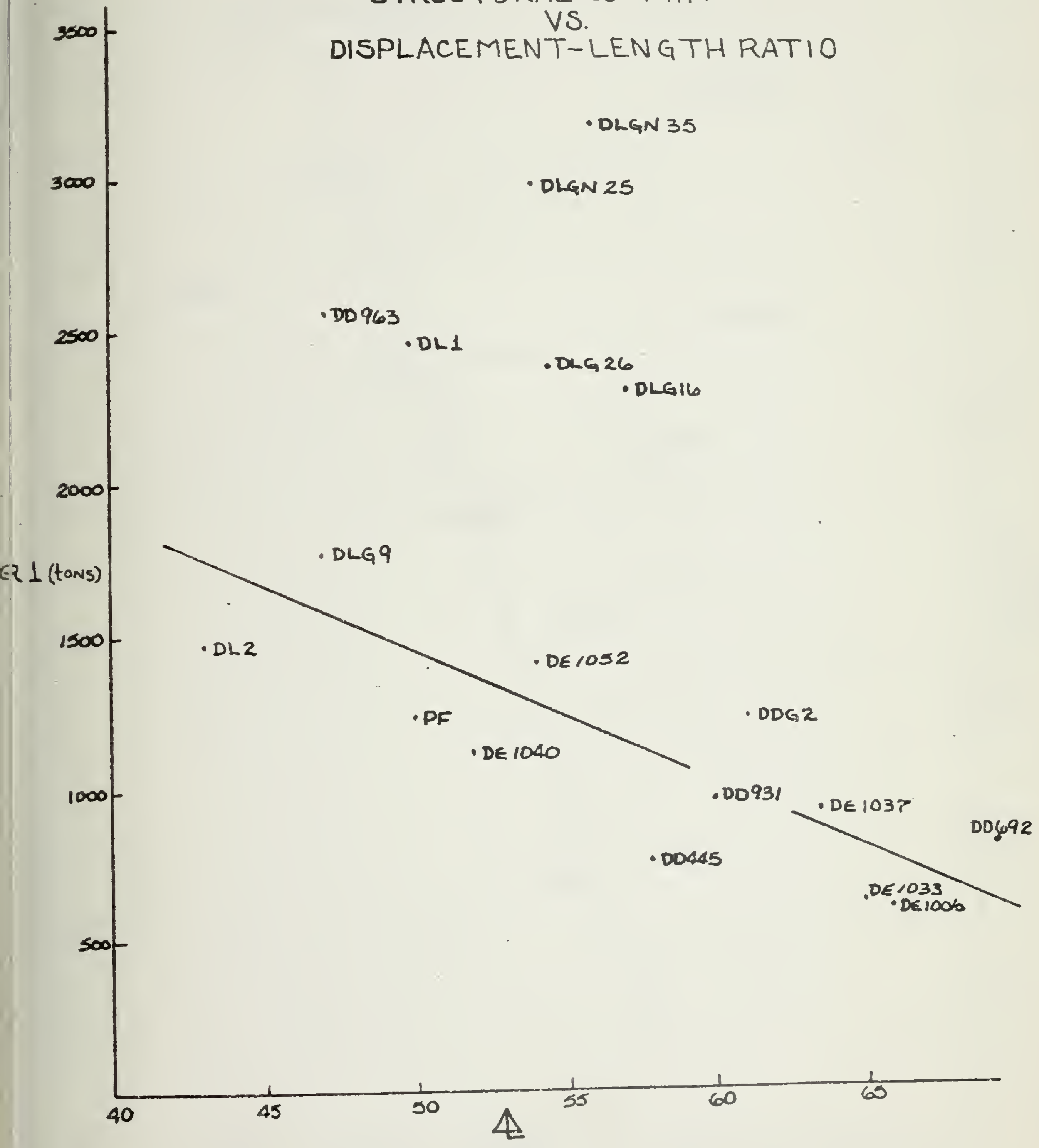
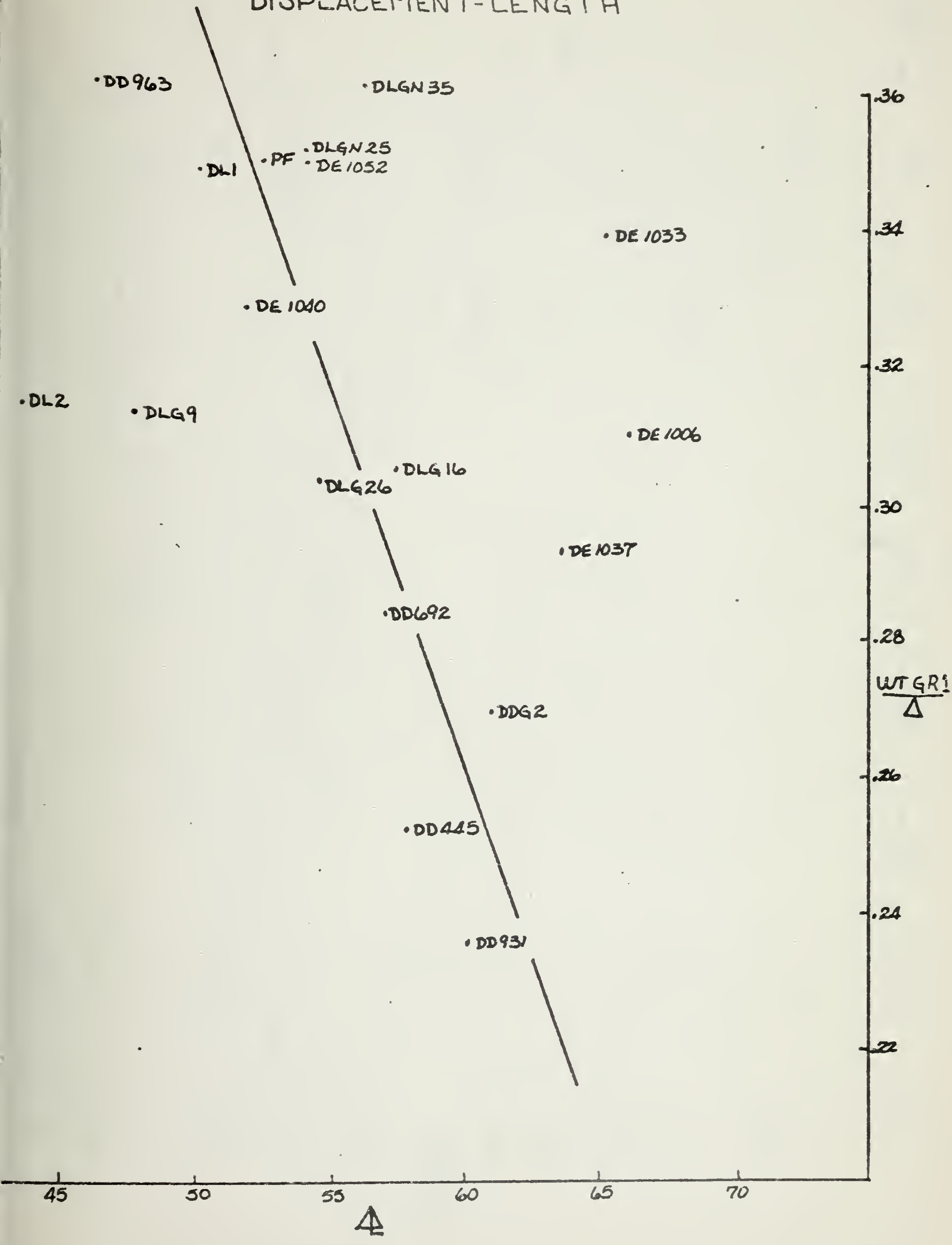


FIGURE 33.
STRUCTURAL WEIGHT PER TON
VS.
DISPLACEMENT-LENGTH



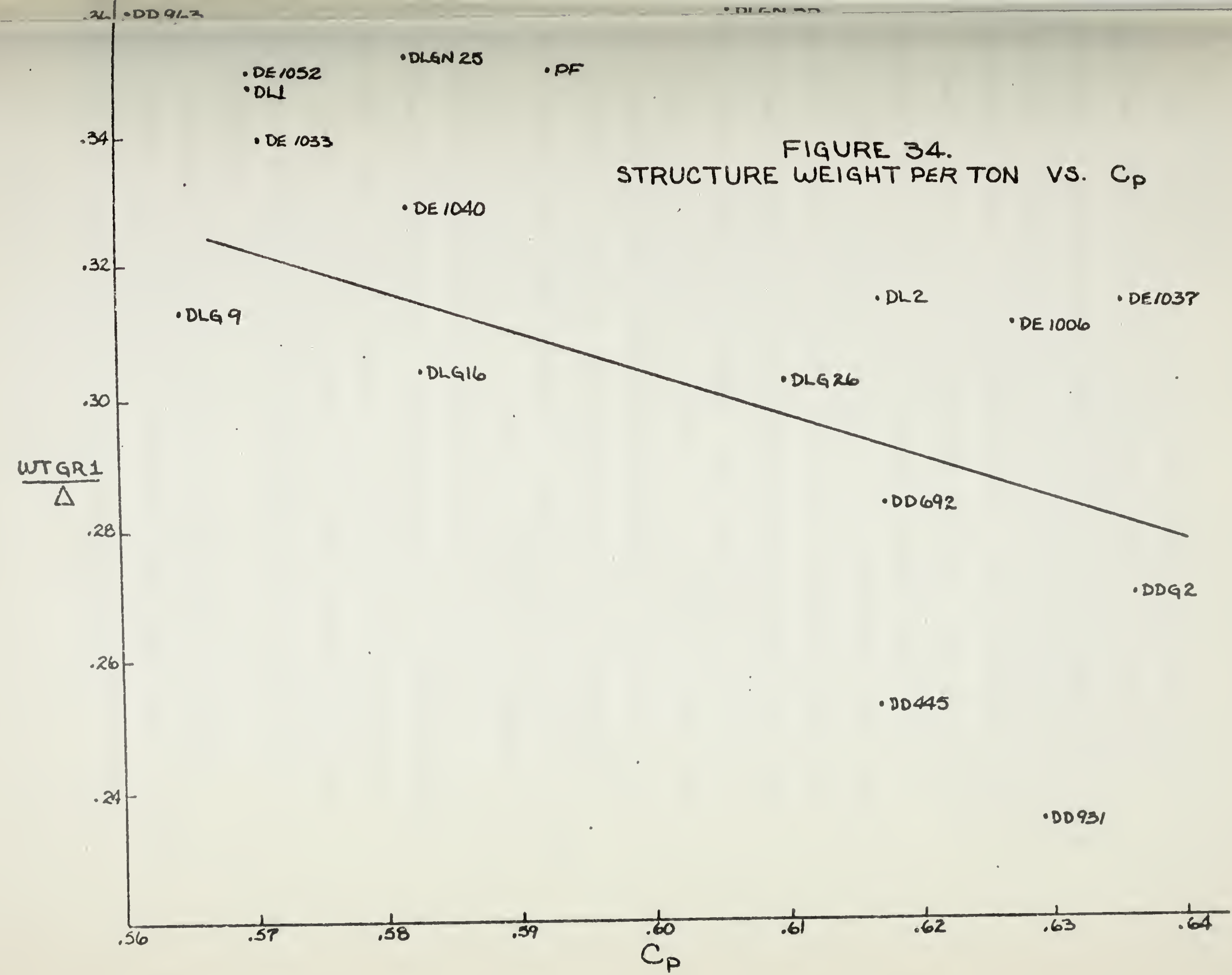


FIGURE 34.
STRUCTURE WEIGHT PER TON VS. C_p

4.1.3 Engineering

The propulsion and engineering weight fractions have been decreasing with time as shown in figures 35 and 36. Although propulsion power and displacement have been increasing with time these weight fraction trends with time seem to imply that displacement has increased faster than propulsion power. However this may not be the case entirely. One can see in figures 37 and 38 that the propulsion weight per horsepower has remained relatively constant for a particular power plant type and size but in figure 39 it can be seen that the total engineering plant weight per horsepower has been increasing with time. Thus, for example, the improvements achieved in steam plants in changing from 600 psi to 1200 psi plants has not resulted in any reduction in propulsion weight per horsepower and has increased the weight fraction of auxiliary and electrical generating components. Again, however the increased auxiliary and electrical weight are a result of increased air conditioning and electric power needs generated by new combat systems and habitability standards(figure 1). Thus the impact of these other systems makes it extremely difficult to evaluate the impact of hull form on the total engineering plant weight. Therefore only the propulsion plant weight will be considered.

In earlier chapters it was mentioned that increasing the length of a vessel will reduce the high speed power requirement and in figure 40 it is seen that the propulsion weight

fraction decreases with increasing length. However the increased length has been accompanied by increasing displacement(figure 31). In recent years(since 1963) the increases in installed horsepower have been marginal for particular ship types. Thus the decreasing weight fraction is more attributal to increases in displacement(figure 41).

Considering the above factors of increasing displacement and length and, for recent years(since 1963), a relatively constant propulsion plant capacity for particular ship types how have we been able to maintain speed? We earlier asked the question of why we have not increased speed but the former question seems more appropriate at this time. We earlier defined EHP as

$$EHP = R_T/\Delta \cdot \Delta \cdot V,$$

thus

$$R_T/\Delta = EHP/\Delta \cdot V \propto SHP/\Delta \cdot V,$$

where

$$SHP/\Delta \cdot V = \text{Specific Power}.$$

If one can decrease R_T/Δ a more efficient hull form has been attained. In figure 42 one can see that specific power and hence R_T/Δ has generally decreased with time. It would appear then that our designers have been developing more efficient hull forms. If speed and power have remained nearly constant in recent years, this implies R_T has also remained constant. Thus the reduction in R_T/Δ with time must be attributed to increases in displacement. The increases in displacement are a result

›f the demands for greater internal volume dictated by increased ıabitability standards and new weapons system. It was shown .n figure 9 that increasing the size of a ship is advantageous. ǀence, designers have produced larger ships as a result of the ıeeds of payload and have by default maintained a nearly constant $_T$.

Considering the combined effects of displacement and .ength one can see in figures 43 and 44 that the propulsion 'raction decreases with decreasing $\triangle$. This trend is supported y the discussion of $\triangle$ on resistance in Chapter 3.

One can see in figure 45 that a specific speed-length atio the lower the value of $\triangle$, the less the resistance oefficient C_{400}. The one exception to this occurs at $/\sqrt{L_{WL}} = 1.4$. However $\triangle$ does not become a dominant factor in esistance until $V/\sqrt{L_{WL}} > 1.4$.(figure 8). Over a range of peeds or speed-length ratio as in figures 46 and 47, one can ee that low values of $\triangle$ are associated with high speed.

Figures 48 and 49 show weak trends of increasing eight fraction with increasing values of C_p and S, where n Table 1 S was defined as $S/\nabla^{2/3}$. Large values of these parameters are associated with full forms and relatively high esistance over most of the speed-length ratio range.

Thus by decreasing $\triangle$, C_p and S one can, for the same ›wer plant, increase speed or alternatively maintain the ame speed and reduce the power plant size providing additional weight and space for payload.

FIGURE 35.
PROPULSION SYSTEM WEIGHT PER TON
VS. YEAR LAUNCHED

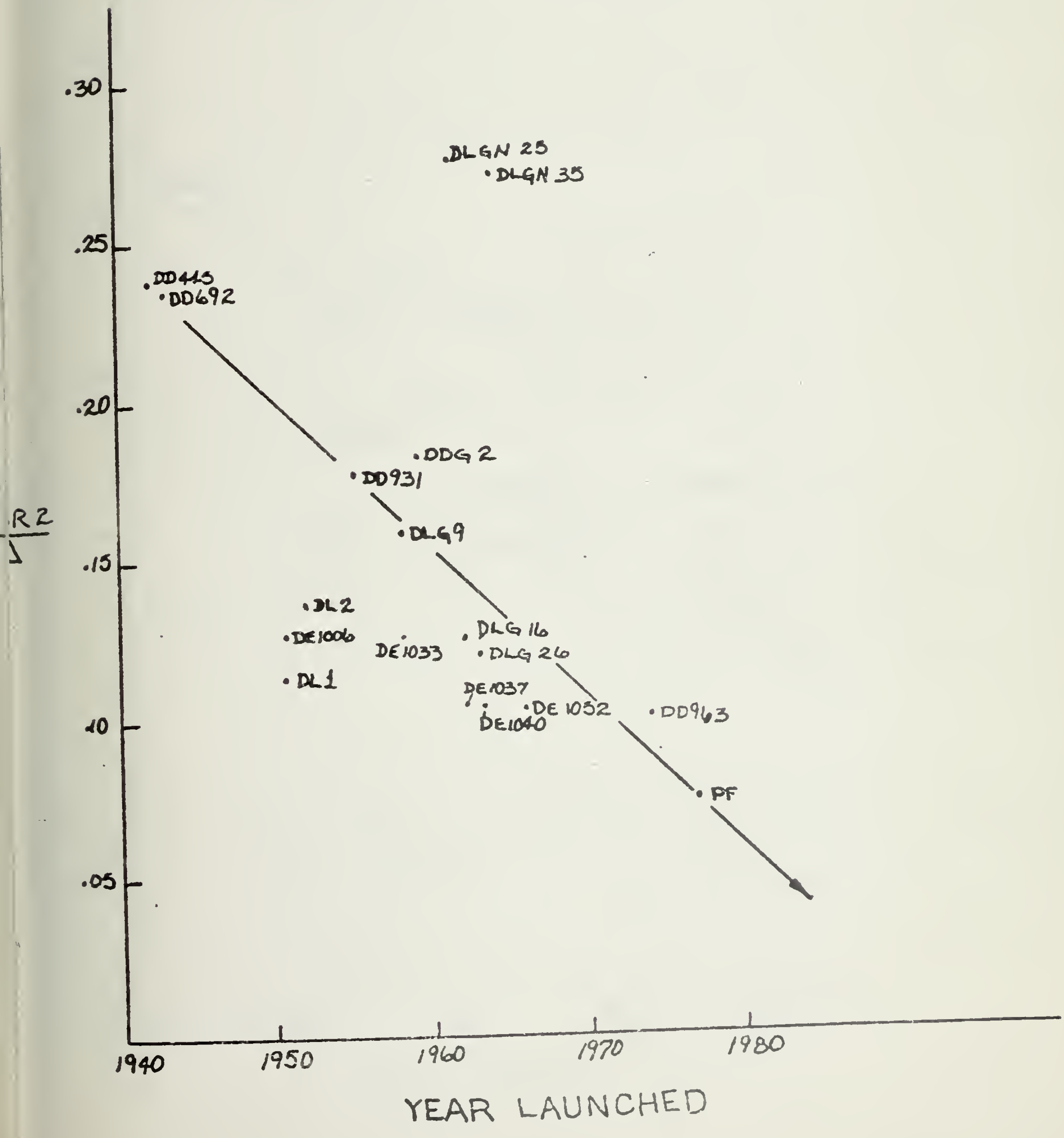


FIGURE 36.
WEIGHT OF PROPULSION, ELECTRICAL, AND AUXILIARY SYSTEMS VS. YEAR LAUNCHED

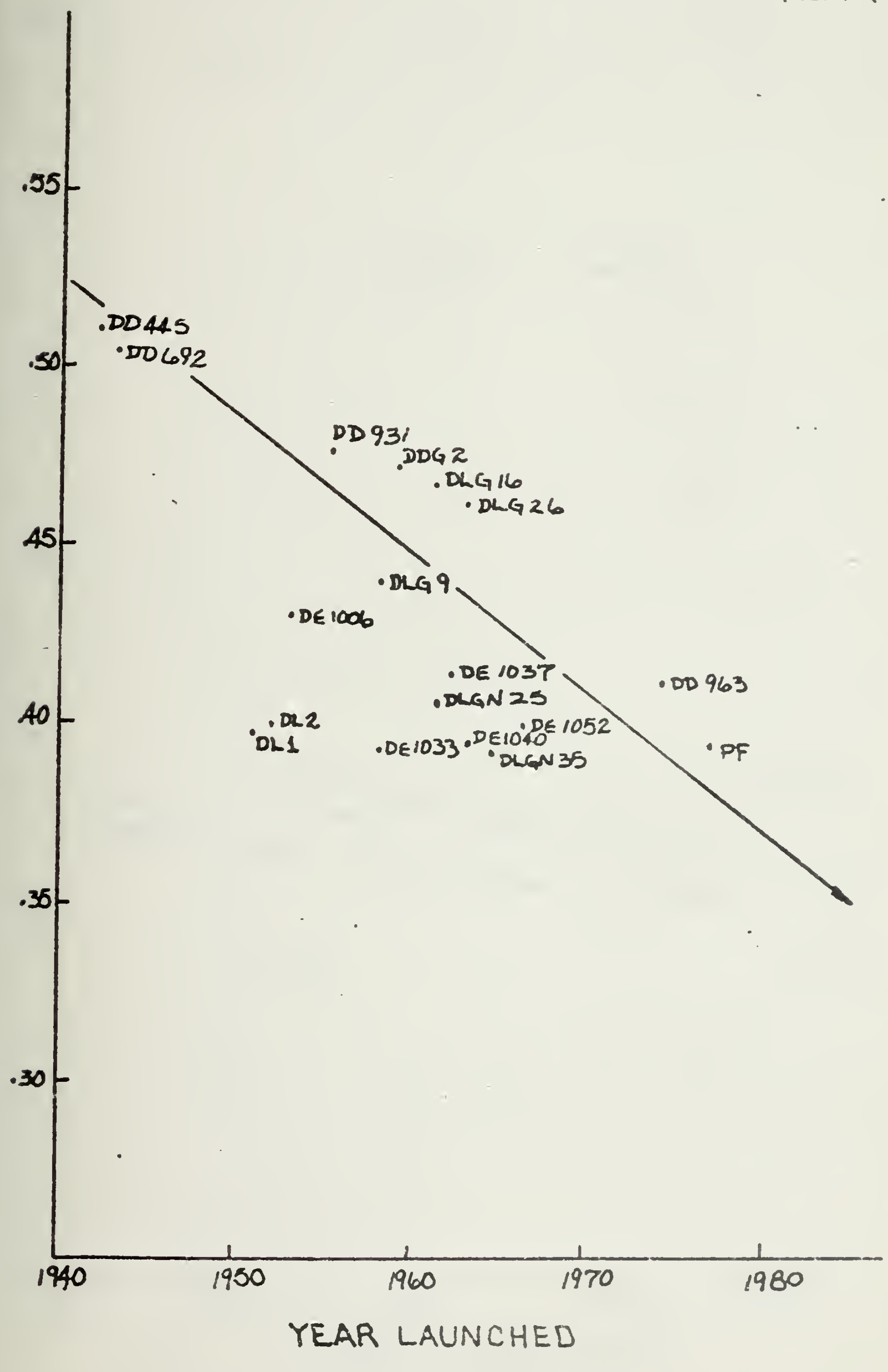


FIGURE 37.
PROPULSION SYSTEM WEIGHT PER SHAFT HORSEPOWER VS. YEAR LAUNCHED

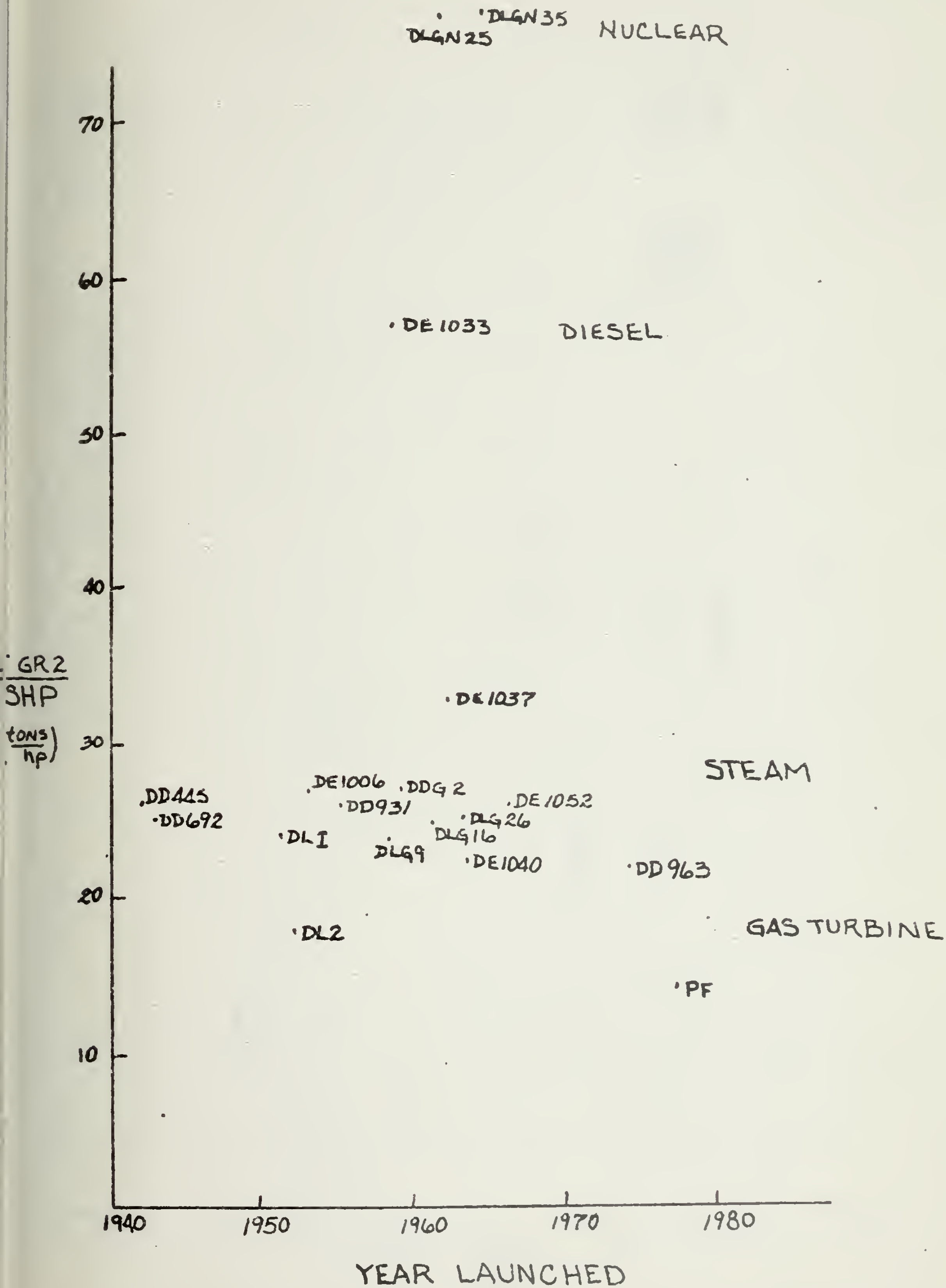


FIGURE 38.
PROPULSION SYSTEM WEIGHT PER SHAFT HORSEPOWER VS. SHAFT HORSEPOWER

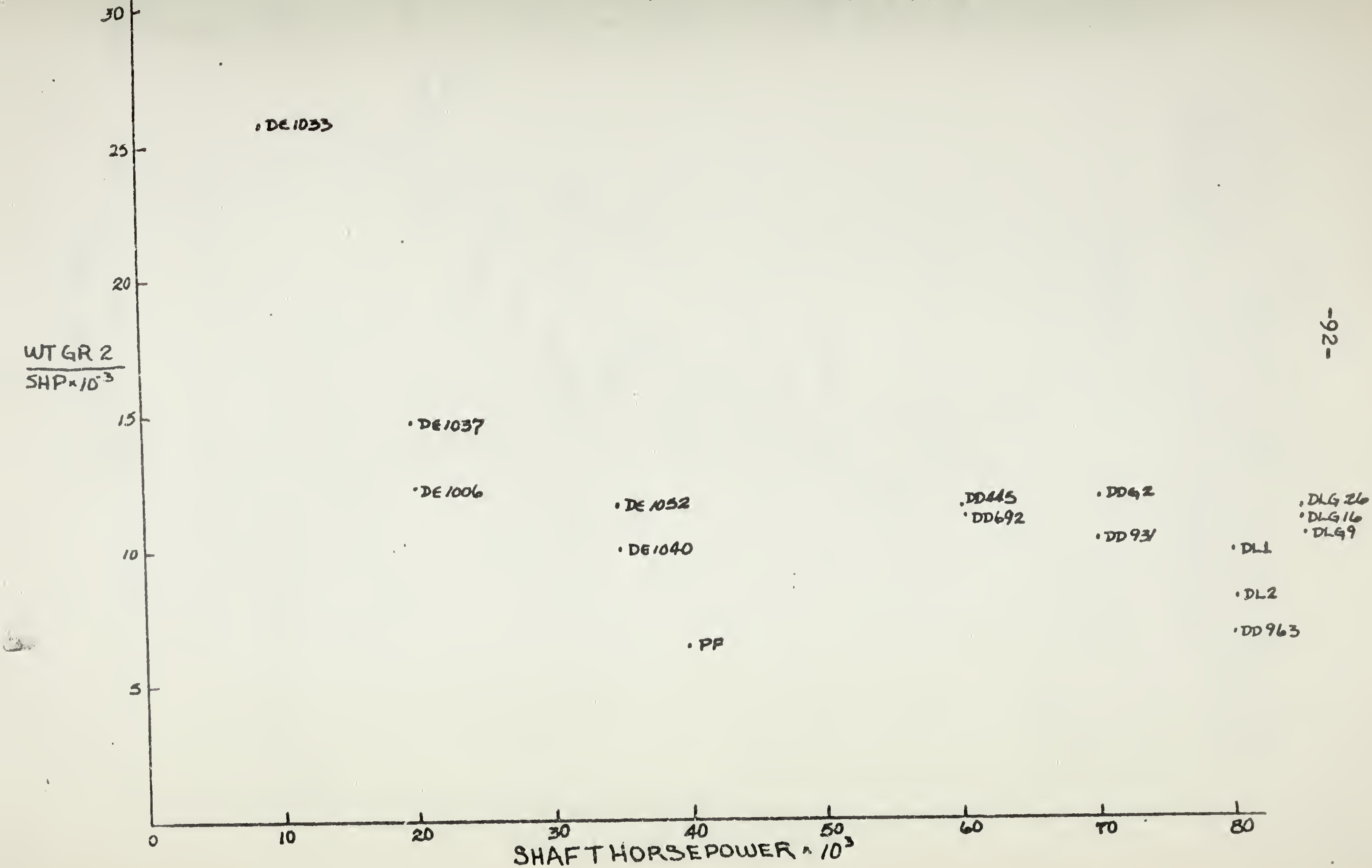


FIGURE 39.
WEIGHT OF PROPULSION, ELECTRICAL, AND AUXILIARY SYSTEMS PER SHAFT HORSE-POWER VS. YEAR LAUNCHED

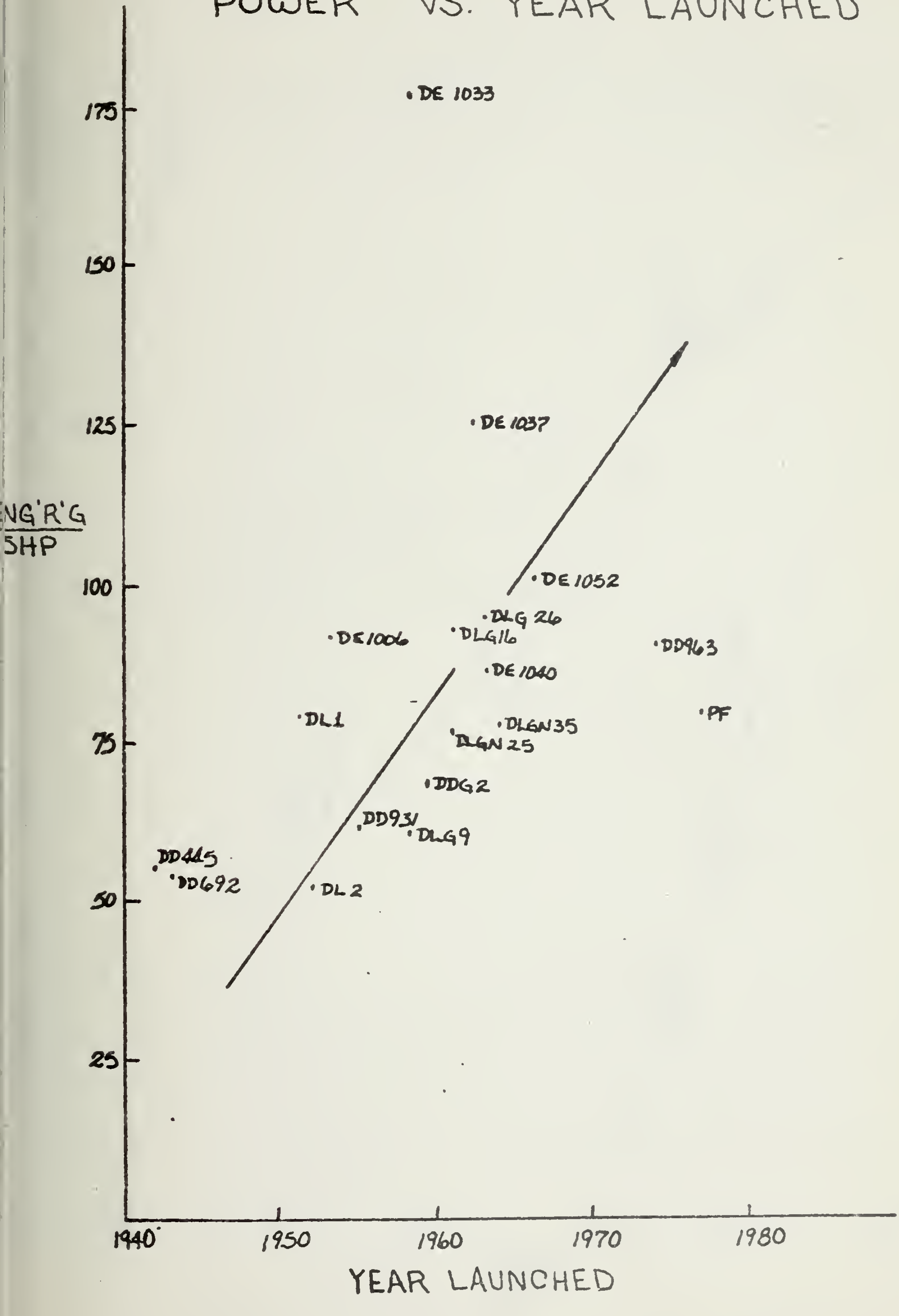


FIGURE 40. PROPULSION WEIGHT FRACTION VS. LENGTH

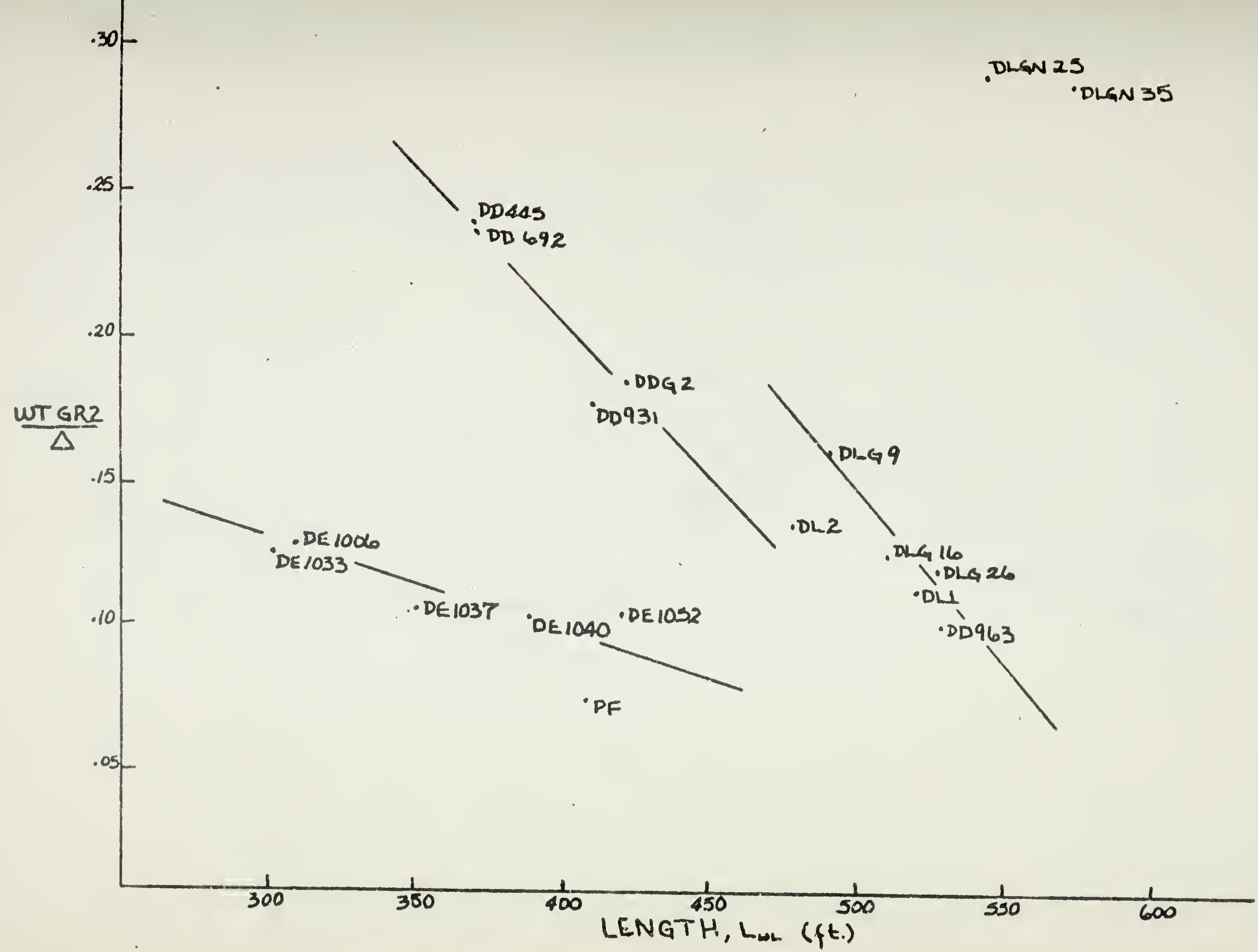


FIGURE 41. PROPULSION WEIGHT FRACTION VS. DISPLACEMENT

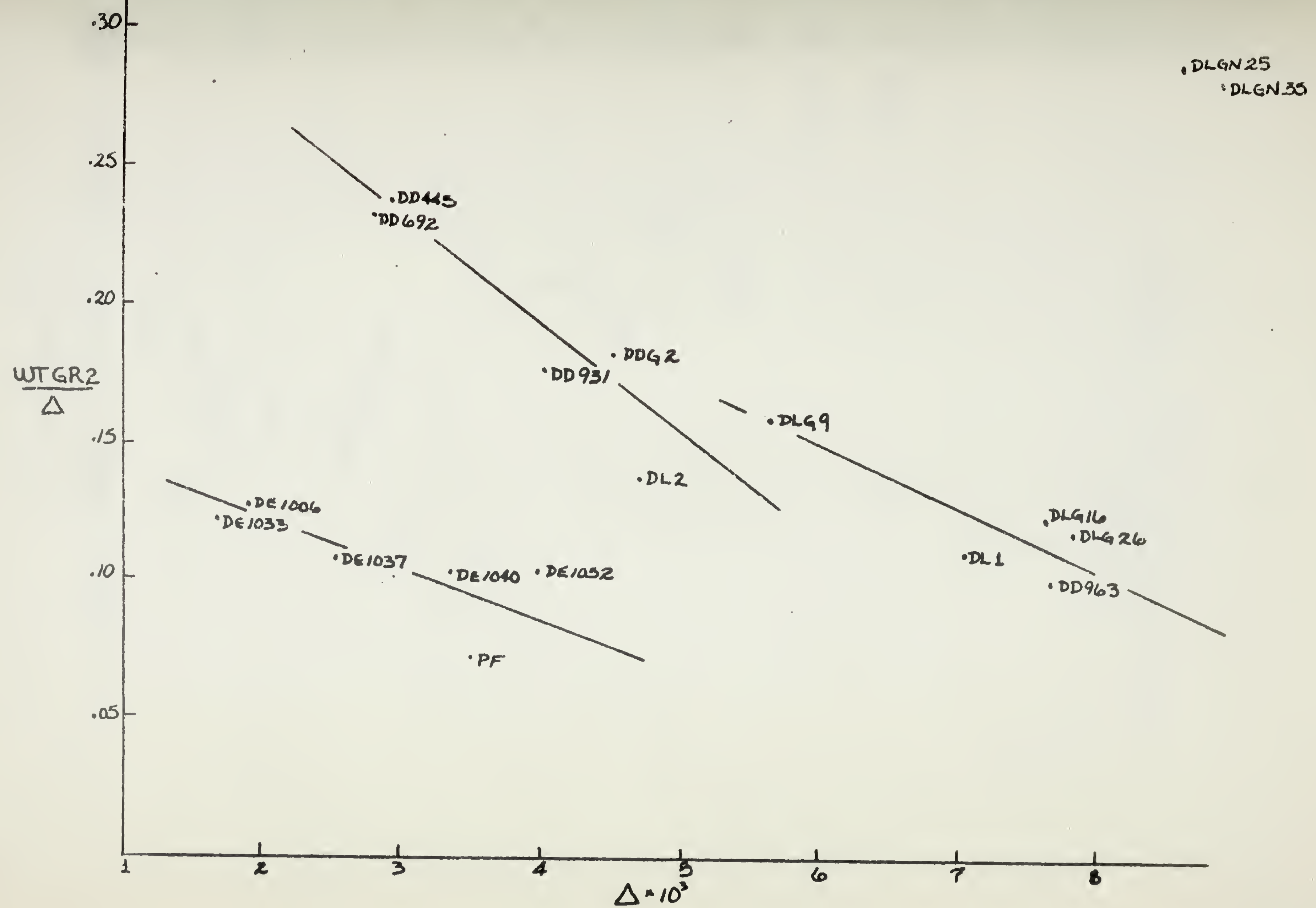


FIGURE 42.
SPECIFIC POWER AT DESIGN SPEED
VS.
YEAR LAUNCHED

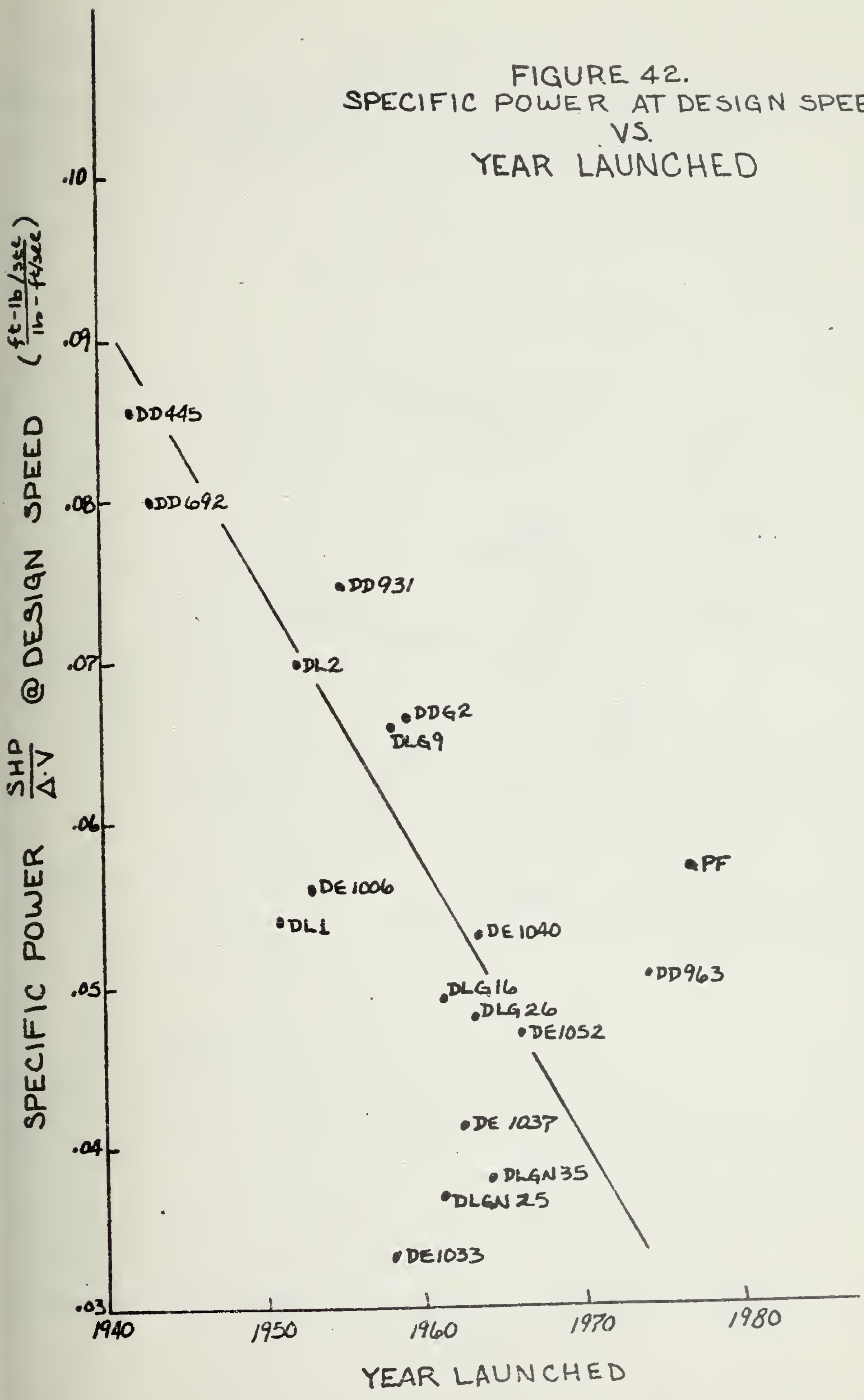


FIGURE 43.
ROPULSION MACHINERY WEIGHT PERSHAFT VS. DISPLACEMENT-LENGTH

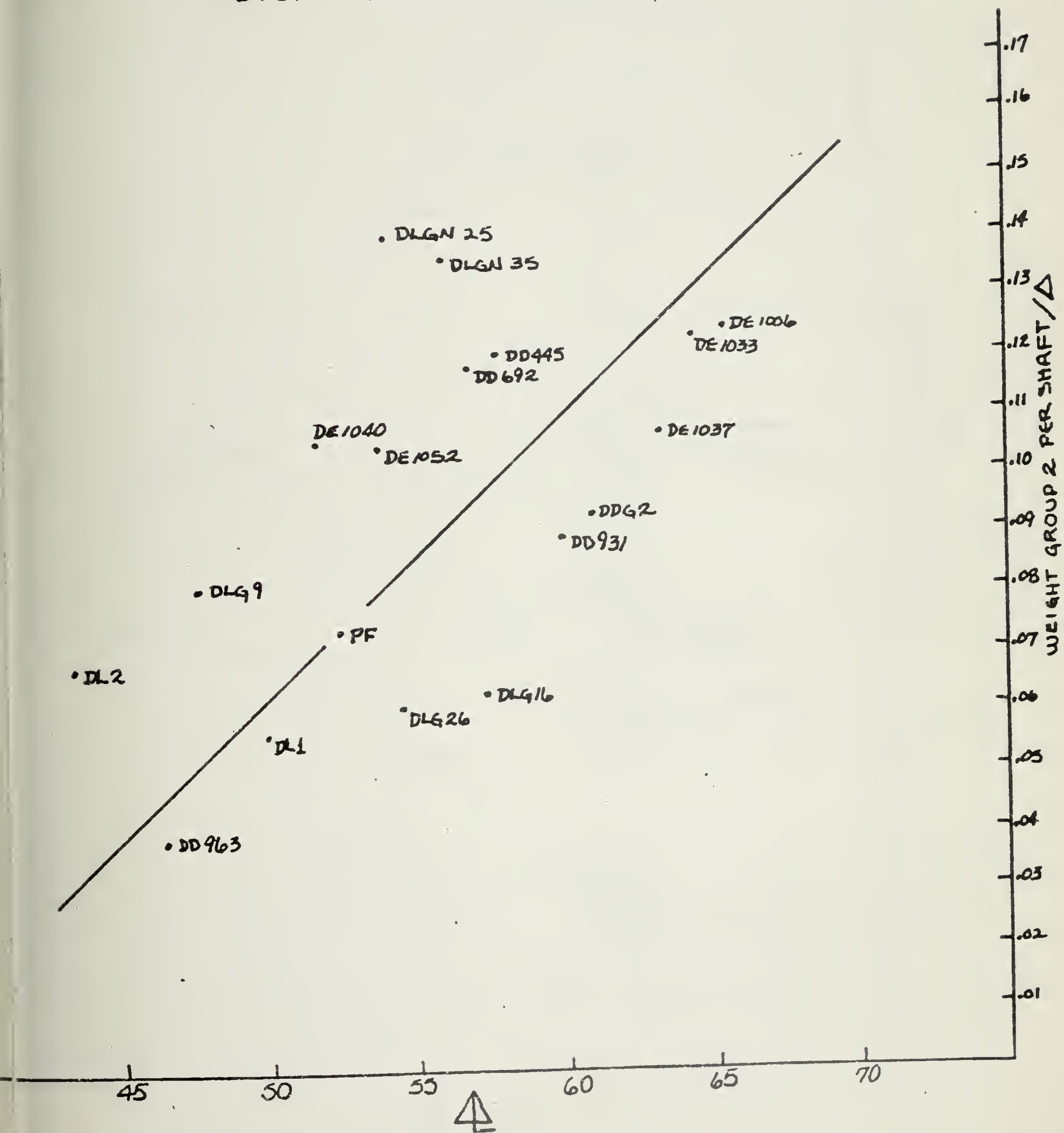


FIGURE 44.
PROPULSION MACHINERY WEIGHT PLUS FUEL PERTON VS. DISPLACEMENT-LENGTH RATIO

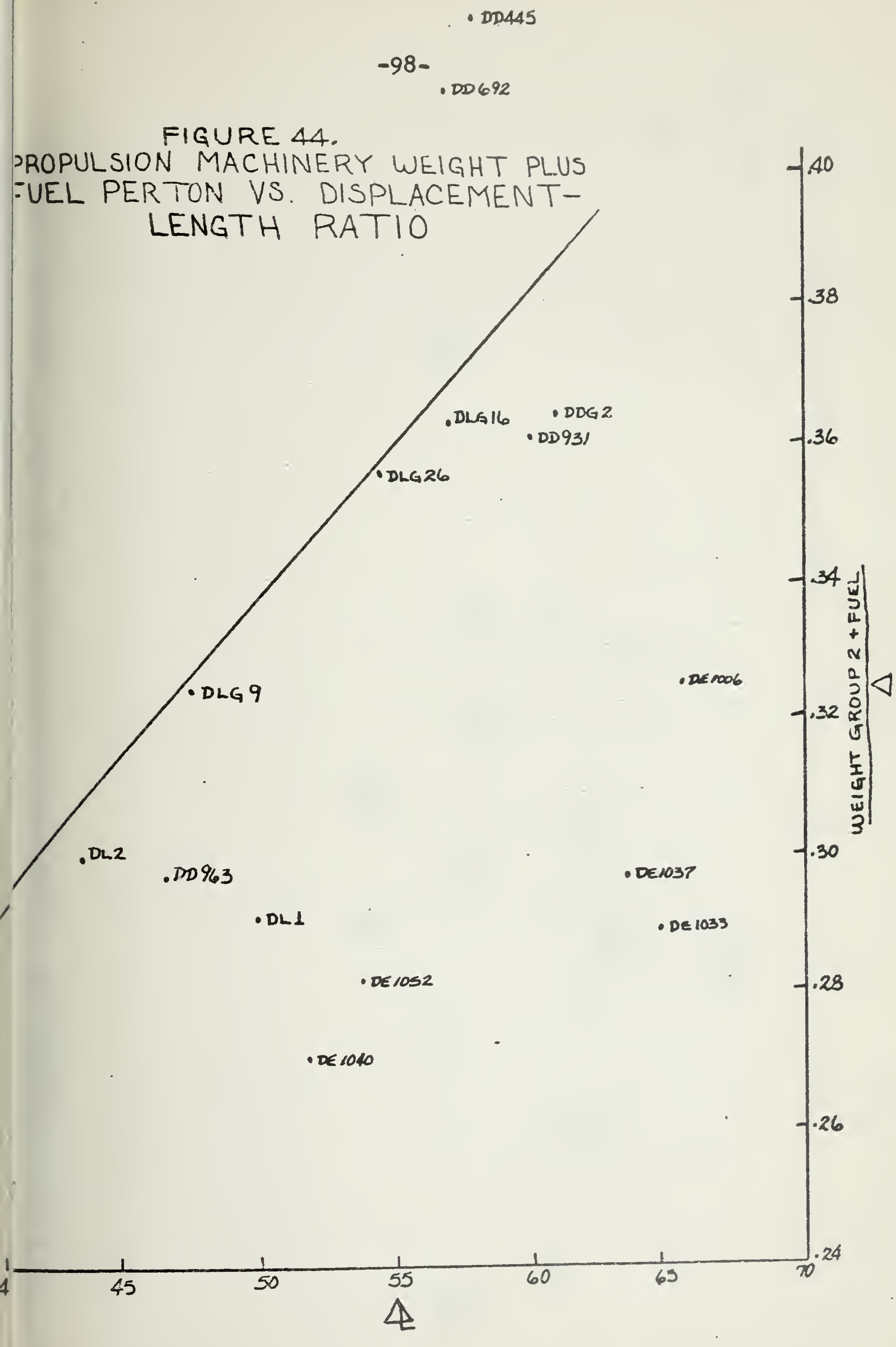


FIGURE 45. RESISTANCE COEFFICIENT, Ⓒ$_{400}$ vs. SPEED-LENGTH

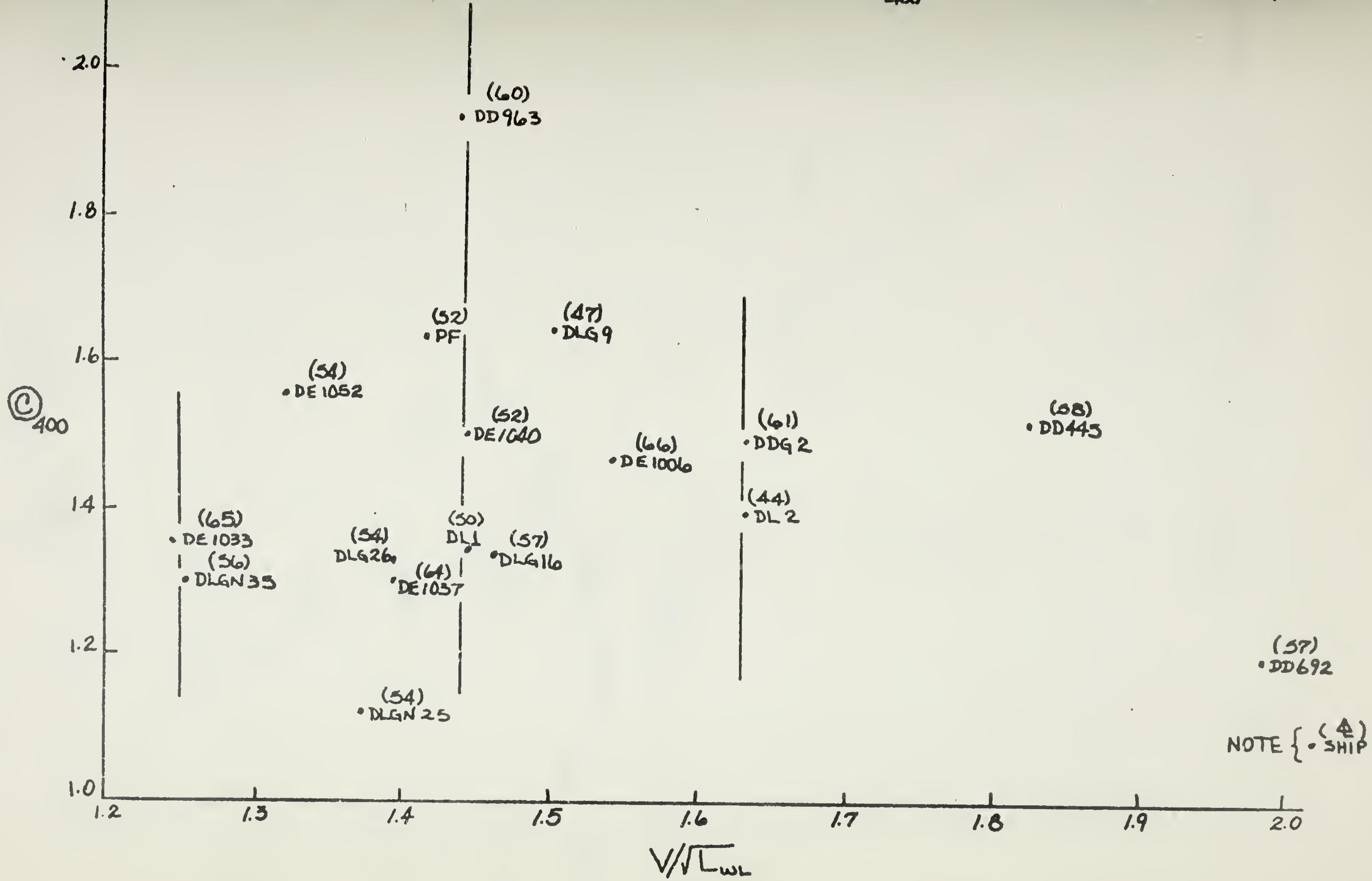


FIGURE 46.
SPEED VS. DISPLACEMENT-LENGTH

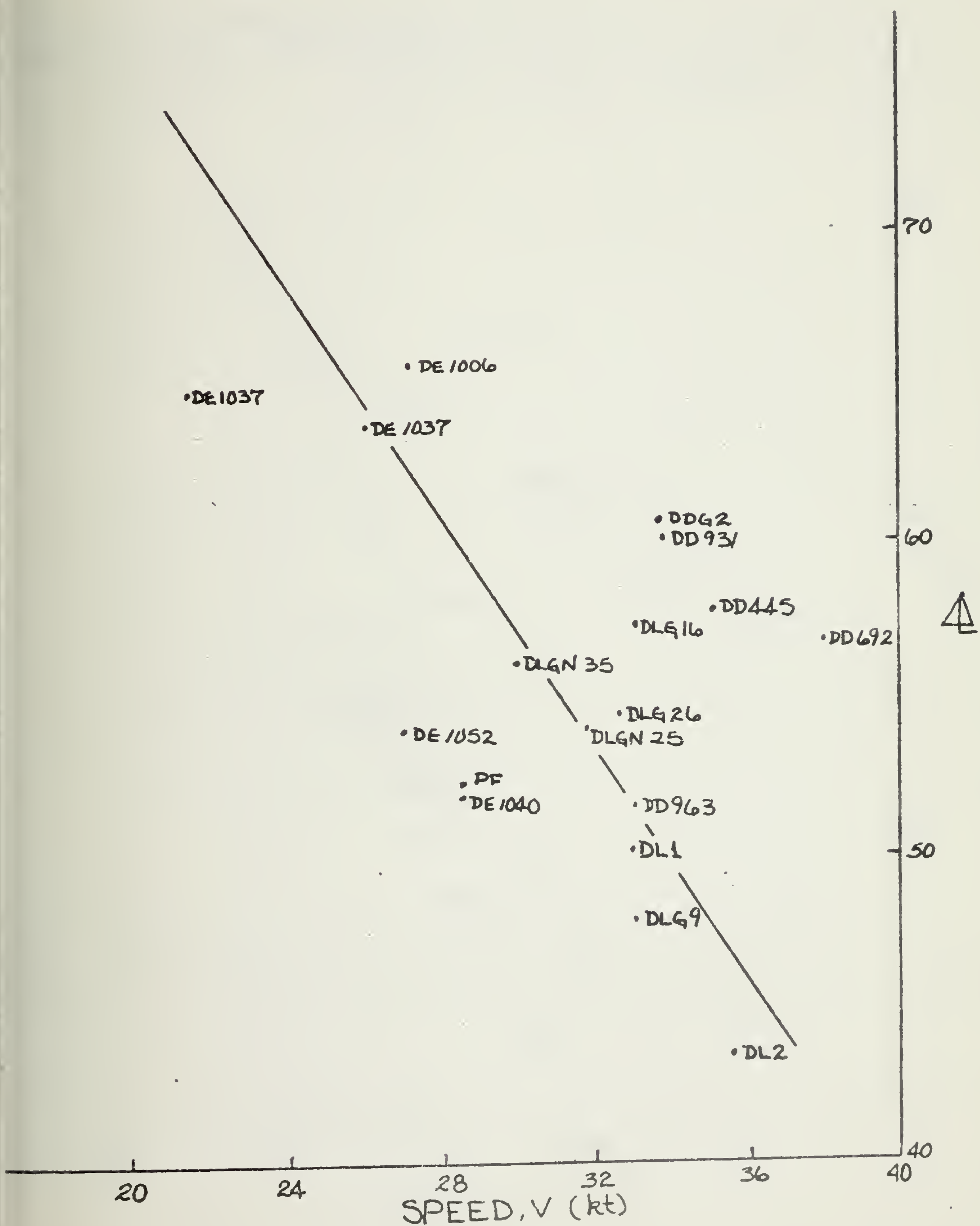


FIGURE 47.
SPEED-LENGTH VS. DISPLACEMENT-LENGTH

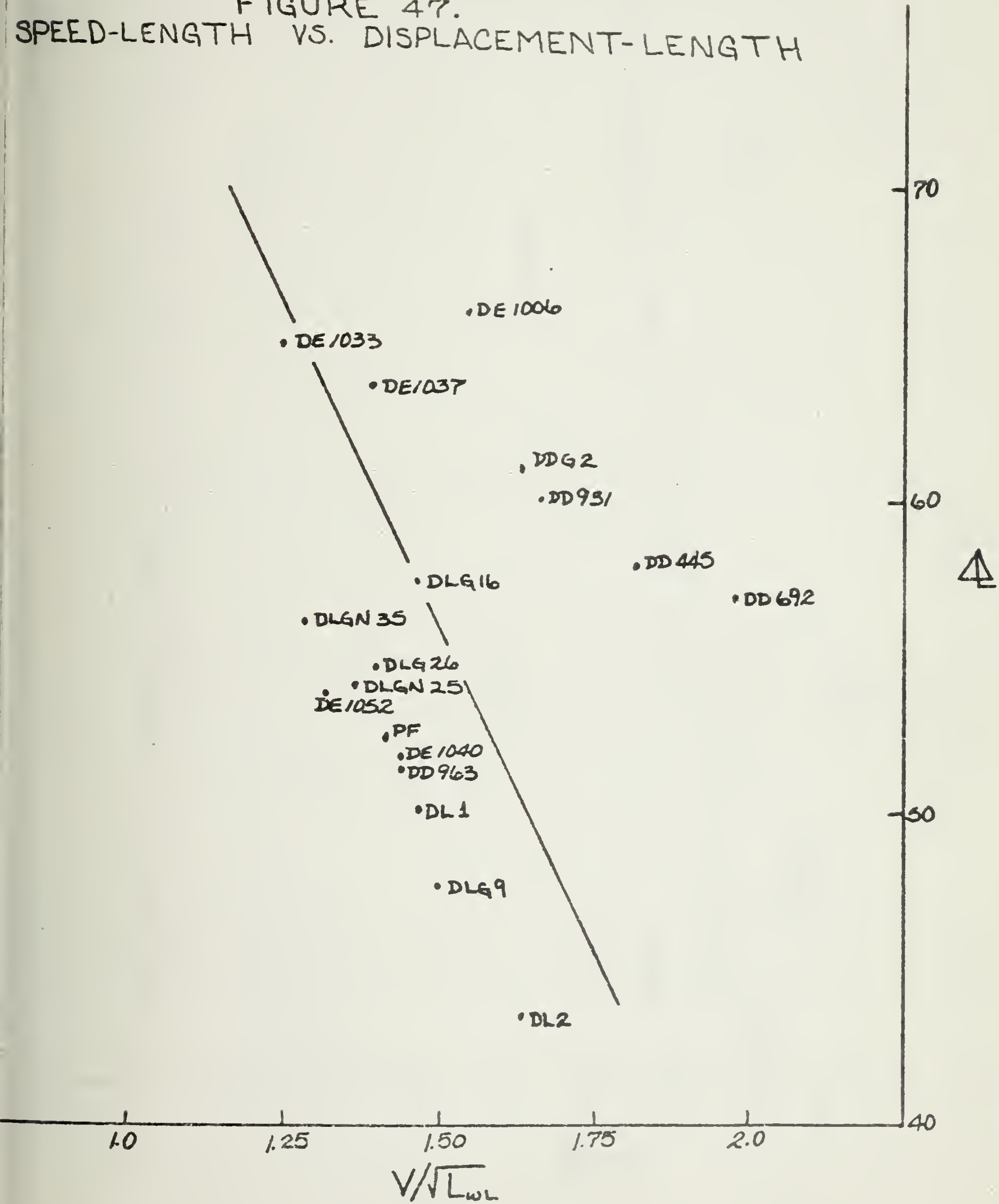
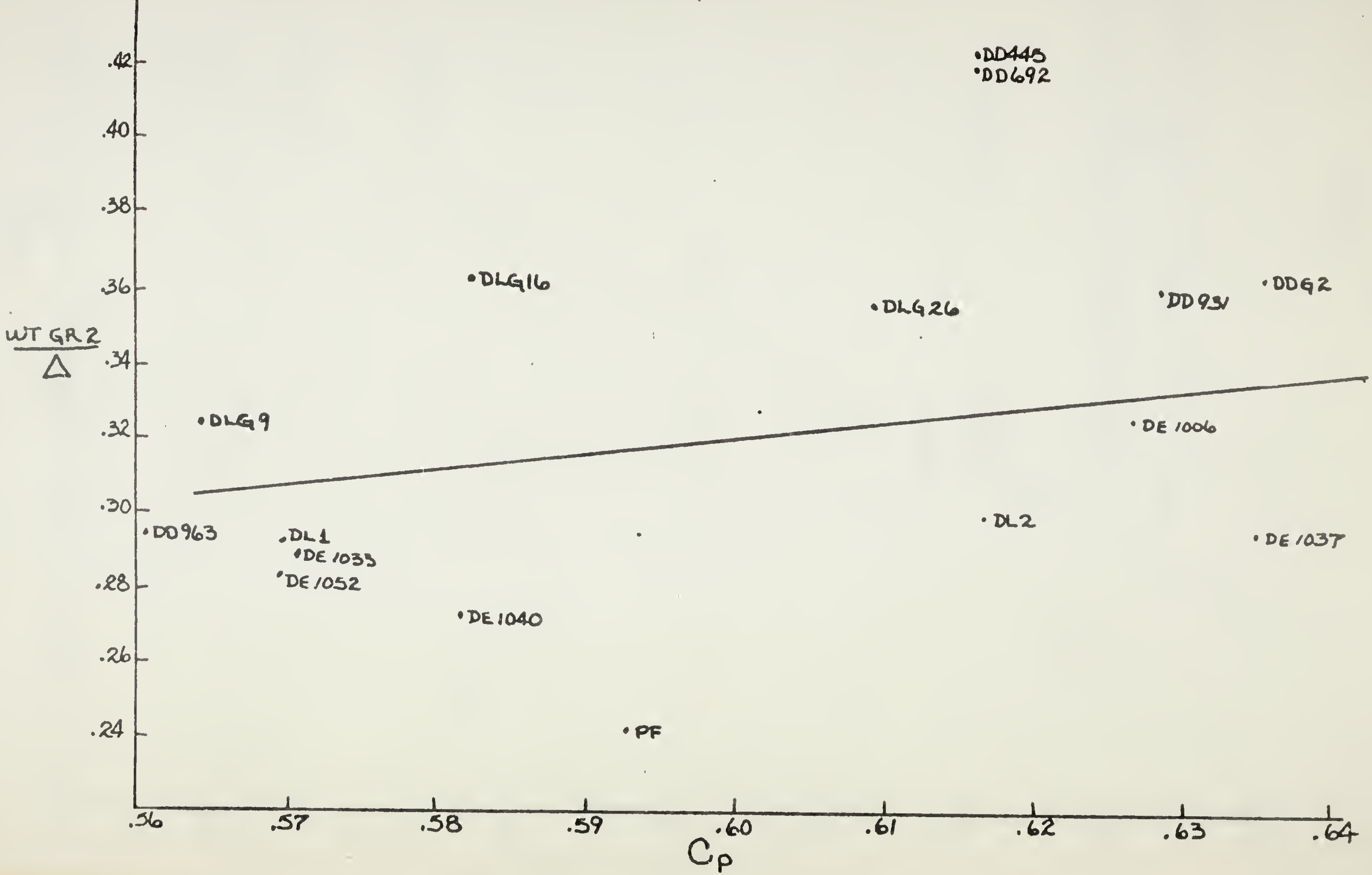
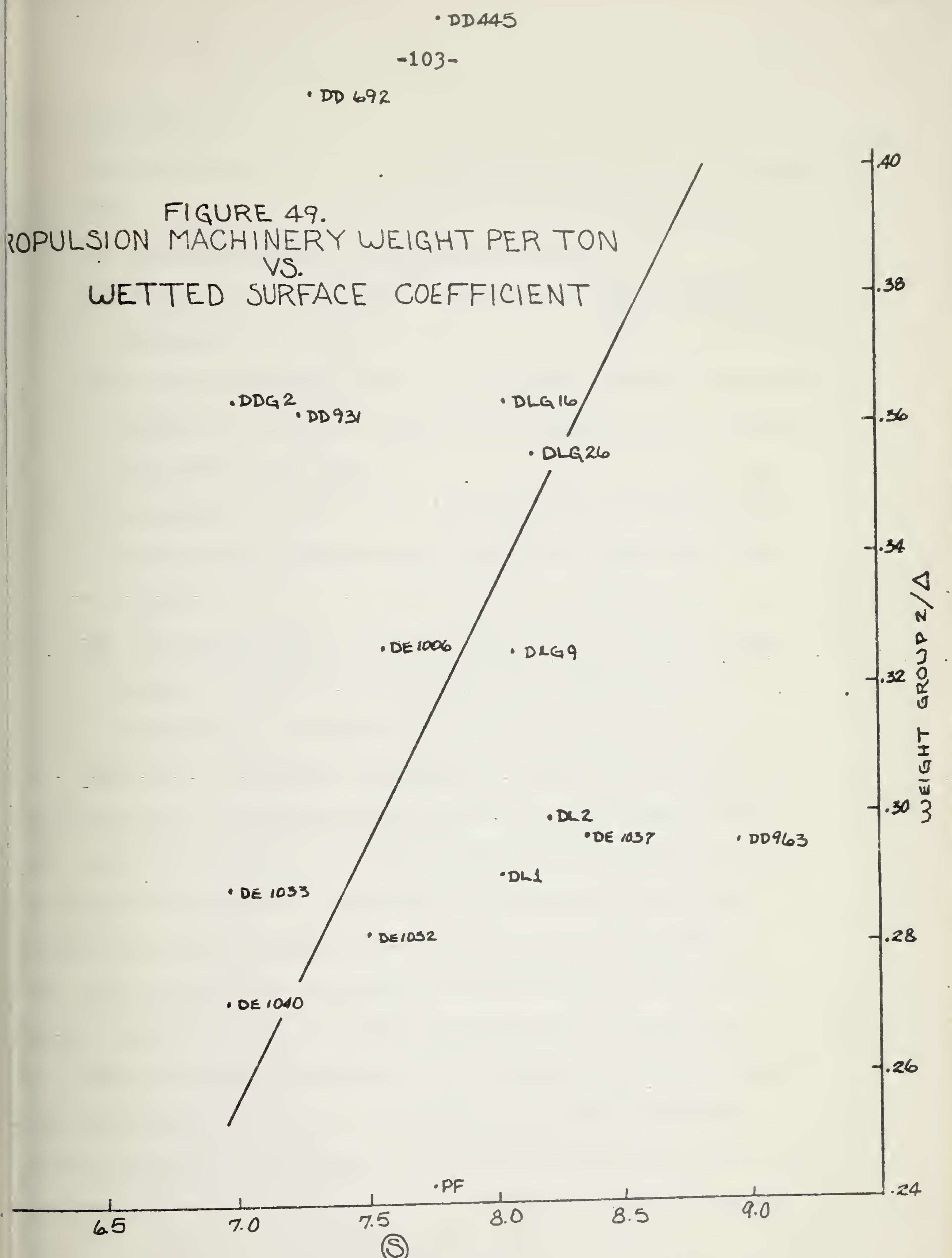


FIGURE 48. PROPULSION WEIGHT PER TON VS. PRISMATIC COEFFICIENT




DD445
DD 692
FIGURE 49.
ROPULSION MACHINERY WEIGHT PER TON
VS.
WETTED SURFACE COEFFICIENT
DDG 2
DD 931
DLG 16
DLG 26
DE 1006
DLG 9
DL 2
DE 1037
DD 963
DL 1
DE 1033
DE 1052
DE 1040
PF
.40
.38
.36
.34
.32
.30
.28
.26
.24
WEIGHT GROUP 2/Δ
6.5
7.0
7.5
8.0
8.5
9.0
Ⓢ

4.2 Endurance

The endurance of a ship is dependent upon several factors. They are:

1) endurance speed - recently 20 knots.

2) fuel load - frequently about 18% of full load displacement.

3) fuel consumption rate - all purpose rates at endurance speed are usually around 0.6 lb./SHP-HR and a function of power plant type.

4) propulsive efficiency - a function of hull propeller interaction forces which ranges in value from 0.55-0.72.

5) hull resistance - a function of hull form and appendages as well as endurance speed-length ratio as discussed in Chapter 3.

The actual endurance capability a ship has is effectively presented as a design constraint early in the design process. The power plant size, and type is selected for design speed. Therefore the impact of hull form on endurance is in determining the power needed to sustain speed and consequently the fuel consumption rate which determines the fuel load required and the internal volume required to store the fuel.

When comparing alternative hull forms, Neal's regression equations[30] may be used to estimate the hull resistance. Then assuming the same power plant characteristics, fuel load, and propulsive efficiency, the difference in endurance miles

between the alternatives can be estimated.

$$\text{Endurance (n.m.)} = \frac{326. \times lb_{fuel} \times PC \times L_{WL}}{SFC \times C_{TL} \times \Delta \times V^2} \tag{7}$$

If we rearrange the above equation,

$$\text{Endurance} = \frac{326. \times lb_{fuel} \times PC}{SFC \times C_{TL} \times V^2 \times 100 L_{WL}^2 \triangle\!\!\!\!\!\perp} \tag{8}$$

one can see that endurance is inversely proportional to $\triangle\!\!\!\!\!\perp$, imply small values of $\triangle\!\!\!\!\!\perp$ will increase endurance. But it is also inversely proportional to the square of length. So the length selected would be more important than $\triangle\!\!\!\!\!\perp$. Also, from Chapter 3, the resistance coefficient is dependent on $\triangle\!\!\!\!\!\perp$ and high values are desirable. The effect of $\triangle\!\!\!\!\!\perp$ on specific power or R_T/Δ is not noticeable in figure 50. But again the fact that endurance is a very controlled design parameter may be influencing the results in figure 50.

Using the available data one can calculate the resistance coefficient C_{TL} using equation 8. Only 1200 psi steam plants were used with an assumed SFC of 0.6 and PC of 0.63. for the results plotted as a function of three hull form parameters C_p, i_E, C_x in figures 51, 52, and 53. These three parameters showed the strongest correlation with the resistance coefficient in the endurance speed-length ratio range of 0.8 to 1.0. It is clear from the figures that no trend is evident. From Chapter 3 and reference [30] this lack of association is not valid. Hence using equation 8 to calculate C_{TL}, though mathematically correct does not yield a valid merit comparison between hull forms due to the influence of design constraints on endurance, endurance speed, and fuel load.

FIGURE 50.
SPECIFIC POWER AT ENDURANCE SPEED
VS.
DISPLACEMENT-LENGTH

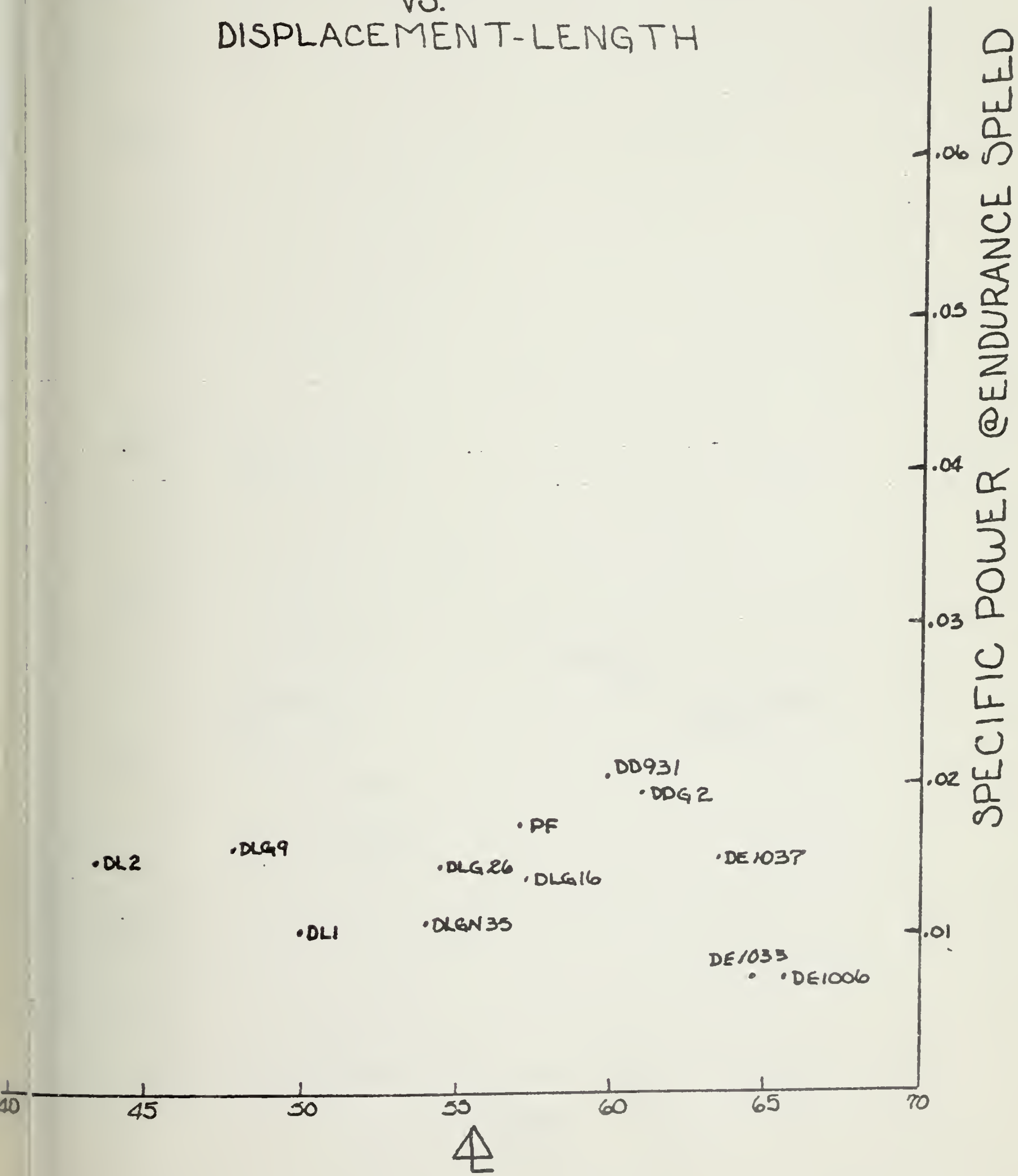


FIGURE 51.
RESISTANCE COEFFICIENT, C_{TL} VS. C_p

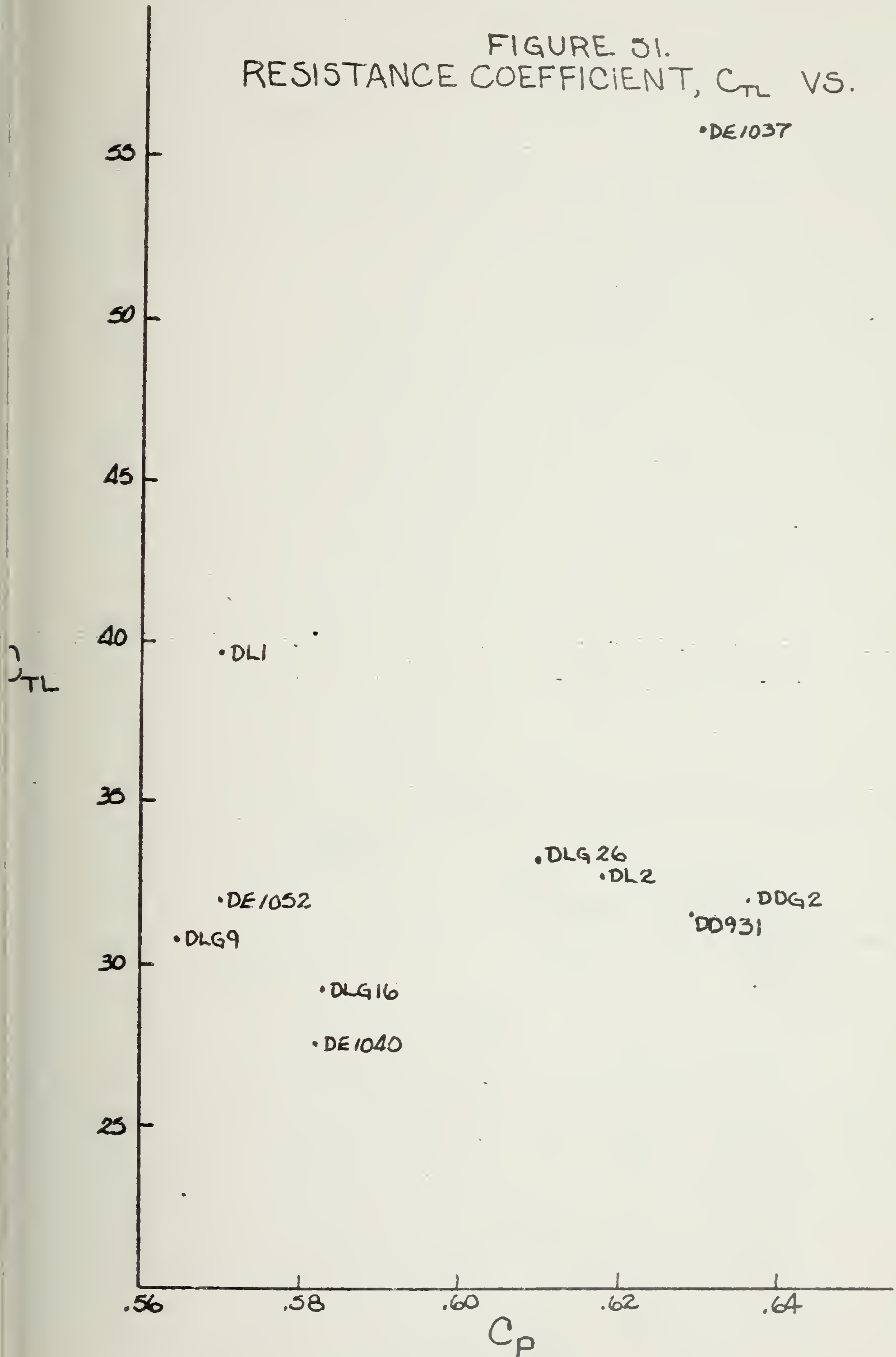


FIGURE 52.
RESISTANCE COEFFICIENT C_{TL} VS. i_E

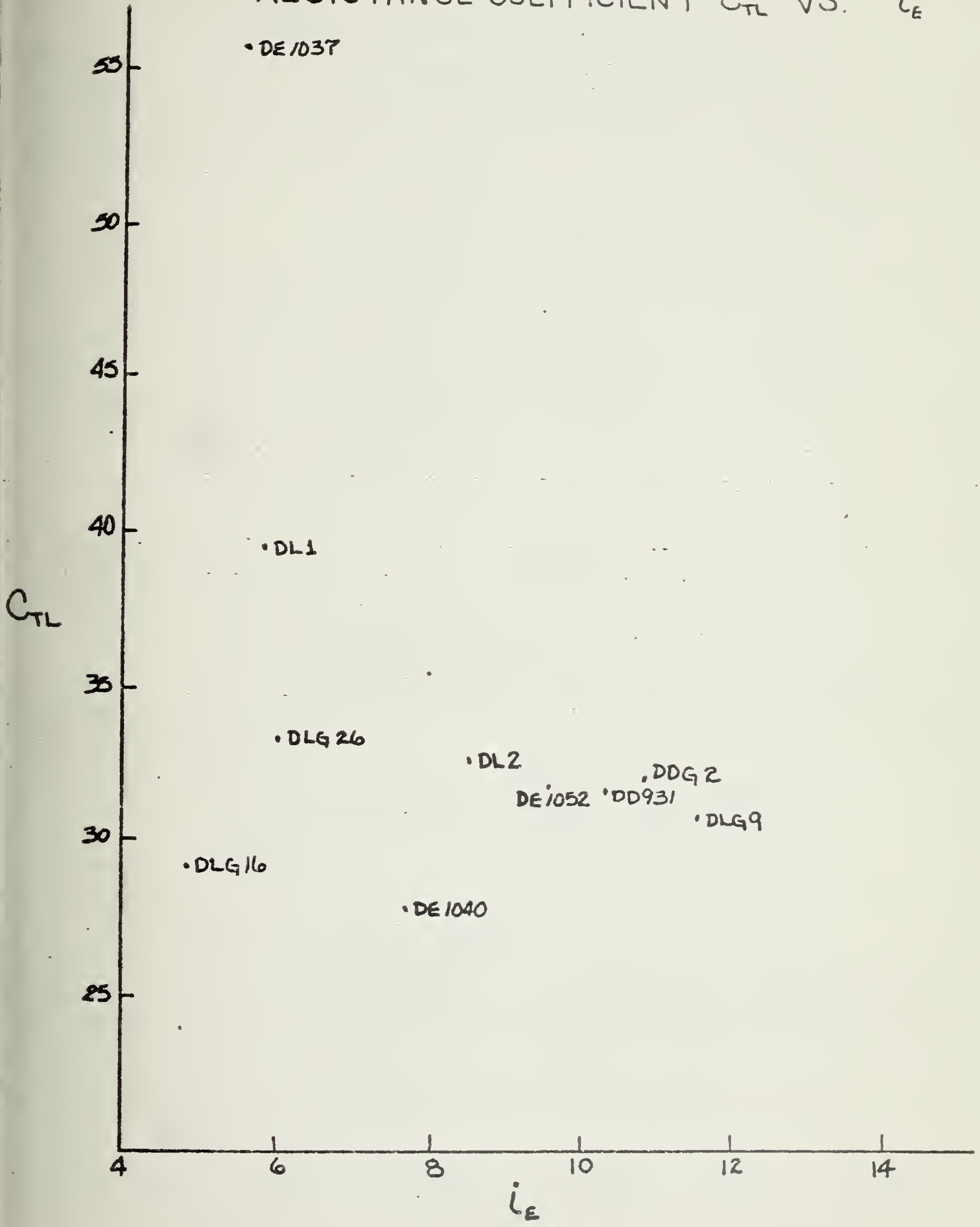
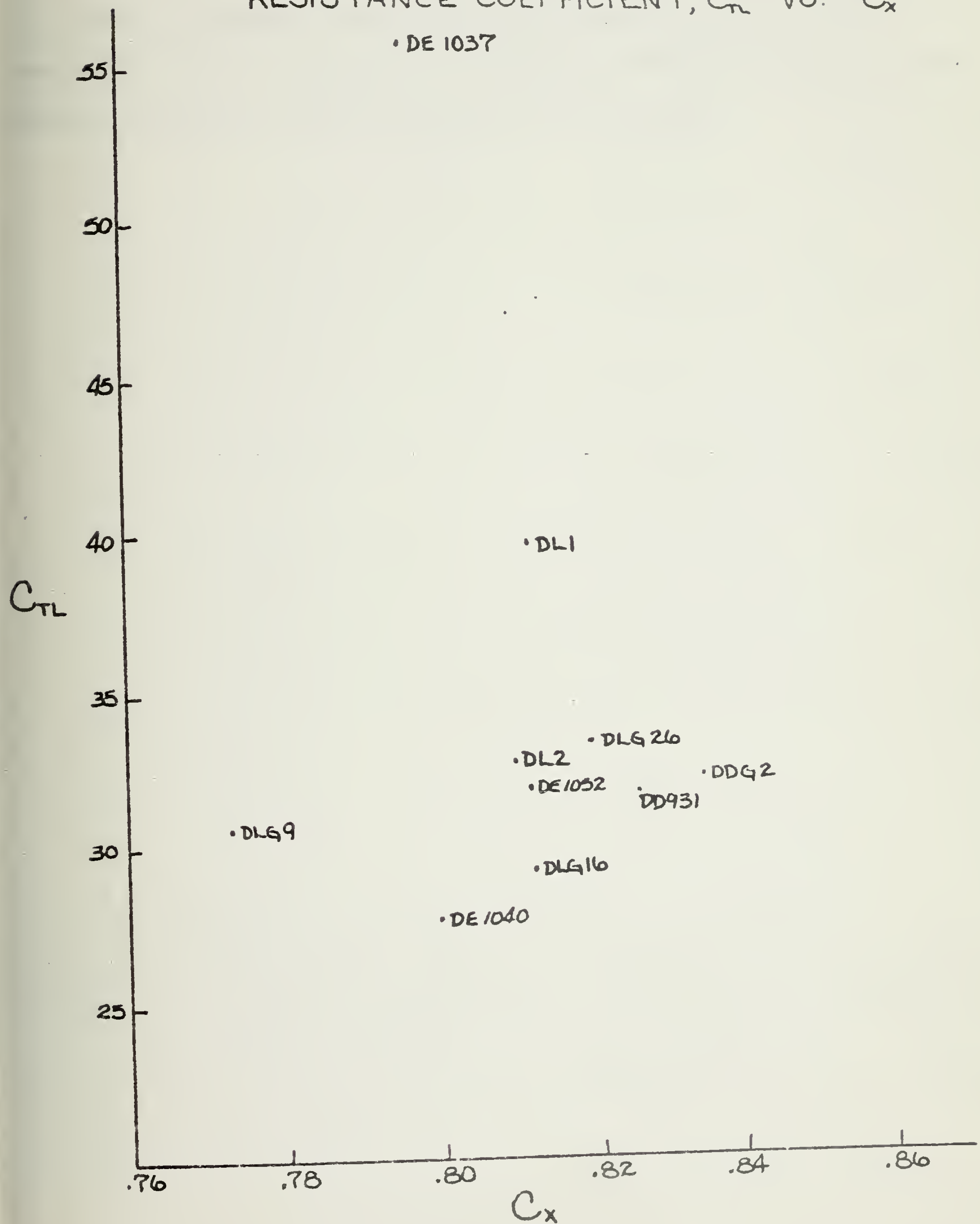


FIGURE 53.
RESISTANCE COEFFICIENT, C_{TL} VS. C_x



Other than model tests, the equations in reference 30 offer the best technique for estimating resistance and comparing hull forms.

Thus it appears that naval ship designers just provide enough fuel for the desired endurance and hence no correlation between endurance and hull form will be evident.

4.3 Intact Stability

The effect of hull form parameters on the stability of a ship can be most easily addressed by considering the mathematical formula used to calculate the metacentric height.

$GM = KB + BM_T - KG$ where,

GM = metacentric height

KB = vertical distance from the keel to the center of bouyancy

KG = vertical distance from the keel to the center of gravity

BM_T = vertical distance from the center of bouyancy to the metacenter

and

$BM_T = I/\nabla$ where,

I_t = transverse moment of inertia of the waterplane

∇ = displaced volume

Increasing the beam will at any angle of inclination cause the ship to rise so that the loss in bouyancy at the waterline is equal to the bouyancy added at both sides. The righting arm is increased by the shift in the center of bouyancy, and the metacentric height is increased because of the large increase in transverse moment of inertia of the waterplane(I_t) and the small changes in the vertical centers of bouyancy and gravity. Figure 54 shows the effect of beam on GM.

Increasing the depth of a ship results in a significant change in the location of the center of gravity. The added

depth requires greater structural weight for shell plating and bulkheads and raises the height of the superstructure resulting in an increase in KG. BM decreases since I_t remains constant and the displaced volume increases. KB increases only slightly. The net result is a decrease in GM with increasing depth.

The effect of increasing draft depends upon how the increase is accomplished. If weight is added high in the ship KG will increase greater than KB. Hence GM will decrease. If the draft is increased by adding weight low in the ship then KG decreases, KB increases slightly resulting in an increased in GM. Alternatively, designing for a deeper draft will also increase GM by permitting weight to be placed low in the ship(figure 55).

By combining the effects of beam and draft on metacentric height in figure 24 we see that GM decreases with increasing B_x/T_x. Apparently the effect of low weight loss by reducing draft is greater than the effect of increasing the waterplane moment of inertia with beam.

Also in figure 56 we see that GM decreases with increasing Δ, C_p, and T_w/B_x. The decrease in GM with increasing Δ may be due to the relatively larger waterplane, whereas the decrease in GM with increasing C_p and T_w/B_x is apparently due to the loss in draft.

It must be remembered that the trends in figure 56 may be as much a function of superstructure and payload as hull form.

FIGURE 54
METACENTRIC HEIGHT
VS
BEAM

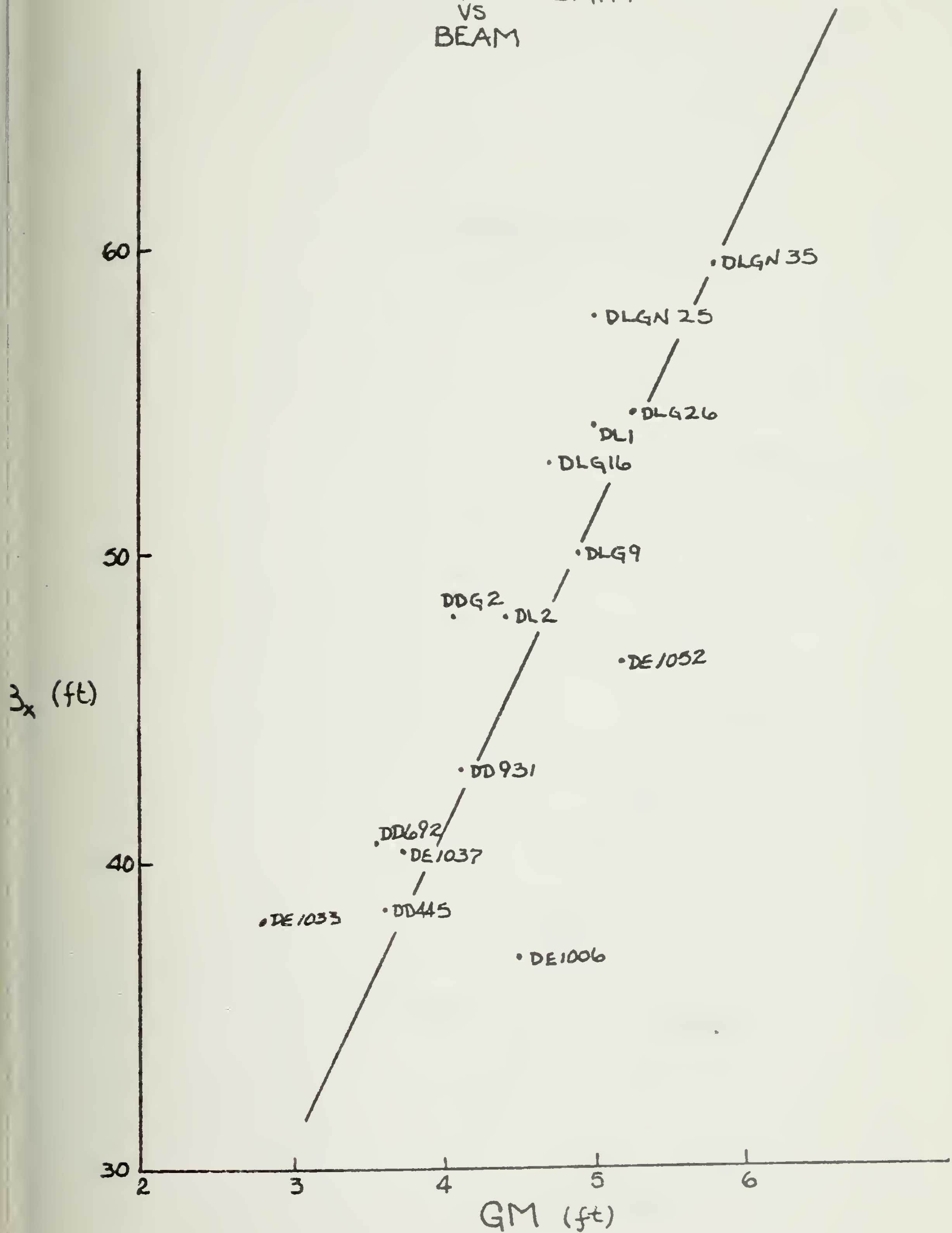


FIGURE 55.
METACENTRIC HEIGHT
VS.
DRAFT

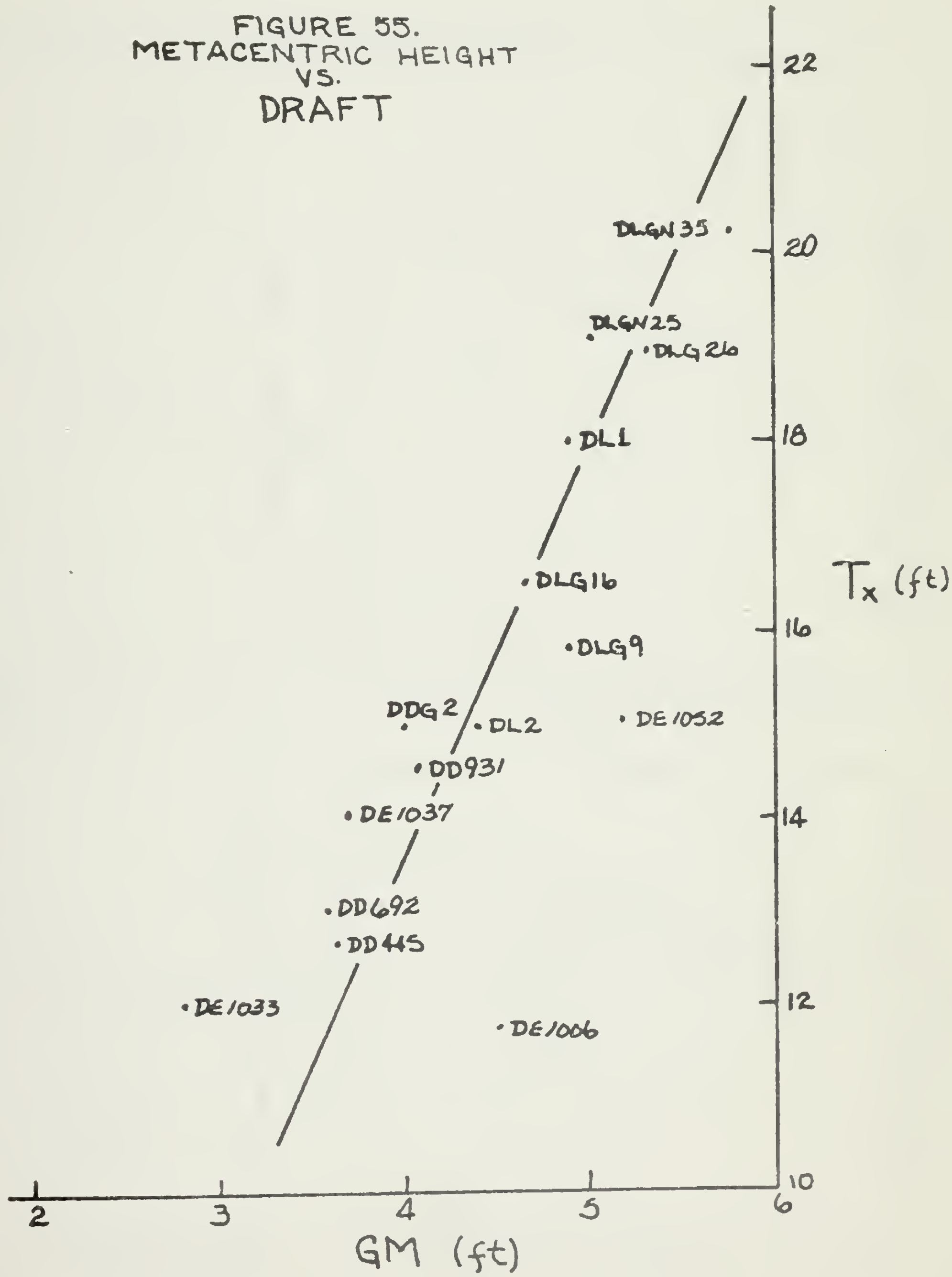
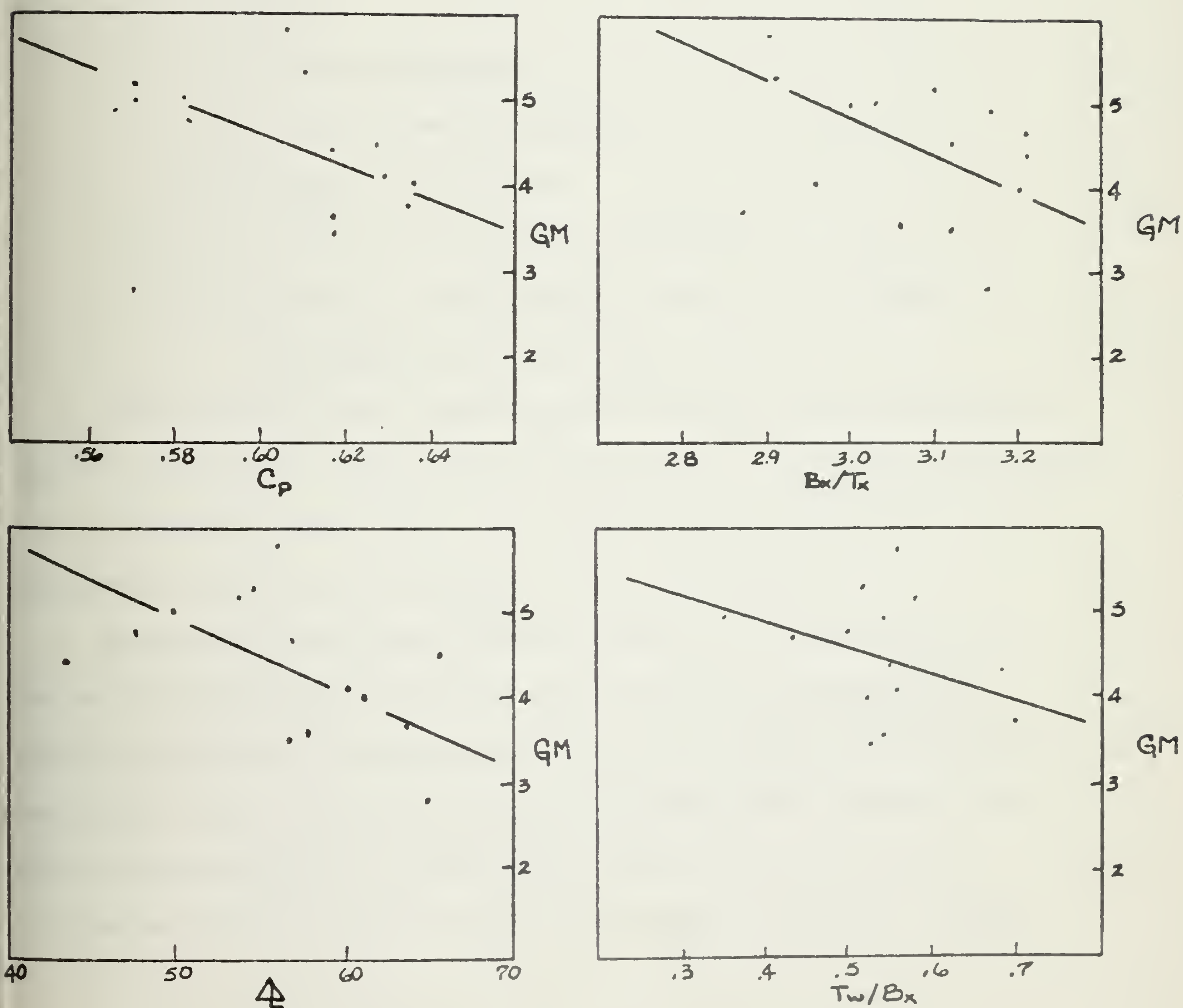


FIGURE 56.
EFFECT OF SOME HULL FORM PARAMETERS ON STABILITY



4.4 Seakeeping

Speed reduction in heavy weather results from two types of influence. The first is the direct effect of the added resistance to forward motion caused by the action of winds and waves. The second may be termed indirect and refers to the necessity of voluntary reduction of power — and hence speed — to reduce the severity of the induced ship motions.

Let us consider the direct effects of waves and winds on increasing the resistance. This added resistance results from the following:

(1) wind resistance

(2) wave reflection effects

(3) effect of rolling

(4) effect of heaving and pitching

(5) finally, the indirect effect of the added resistance on propulsion.

The effect of wind resistance on ships is well documented [6], for many ship types and is primarily a flat plate frictional and separation drag. The ship with larger freeboard and superstructure will have the greater wind resistance.

Havelock investigated the increase in a ship's response caused by the combined action of waves and of heaving and pitching motions. An assumption he used in his investigation, which was later verified by Froude and Kriloff, was that the added resistance due to wave reflection is small compared to the resistance caused by the variation in bouyancy distri-

bution. From this Havelock developed an equation to express the mean retarding force on a ship[17]. This equation states that the resistance added by waves and wave caused ship oscillations is proportional to the square of the wave height and nearly independent of ship speed, but strongly dependent on the encounter frequency. More recently, however, it was observed that the more slender a body the greater the deviation from the square rule there seems to be[38].

It has been observed that a rather small variation of wave resistance occurs with changes in wave length. Changing a ship's course, which modify the apparent wave length, can be expected therefore, to have a rather small effect on the resistance. Furthermore, the course must be altered in excess of 40° in order to get a tangible reduction in the added resistance, whereas the character of the ship's motion will be completely changed with a smaller deviation. Thus the loss in sea speed is somewhat independent of course; hence improvement lies not with navigation but with design.

The principle features of a ship design that influence its seakeeping ability are: length, L_{WL}/B_x, Δ, B_x/T_x, C_p, C_x, and freeboard. Ship size and hull form or shape are the two features which impact most on seakeeping ability. A ship's size, particularly length and displacement has the greatest influence on its seakeeping ability. Generally, a large ship reacts less violently in a given sea state than a smaller ship, except when subjected to swells of particular wave lengths

which cause a resonant response. It should, therefore be expected that the pitch and, heave motions, and hence the slamming and deck wetness characteristics of 550 foot, 7500 ton frigate would be considerably superior to those of a 400 foot, 4000 ton destroyer escort.

The influence of a ship's hull form on its seakeeping characteristics can be best understood by separately considering its underwater and above water characteristics. It is the underwater hull form that principally influences the pitch, heave, and roll motions of a ship as it reacts to a given seaway. Such hull form features as length, draft, beam, prismatic and midship section coefficients, longitudinal centers of bouyancy and flotation, as well as the addition of bilge keels, active fin roll stabilizers, or a bulbous bow influence a ship's motion to varying degrees, These same factors also strongly influence a ship's resistance to forward motion, its maneuvering ability, and its intact and damage stability characteristics.

Once a ship's underwater hull size and form have been established in the design process, the ship's motion and slamming characteristics in a seaway have been largely predetermined. Nevertheless, the ship's above water shape, while it does not significantly influence the ship's motion, does strongly affect its spray and deck wetness characteristics. The freeboard near the bow, particularly at the forward perpendicular, is the most important aspect of the ship's above water shape with

respect to taking green water aboard. Other features of a ship's above water shape, which primarily affect its spray characteristics, are the flare of the bow, the use of a knuckle or spray rail in the bow, and the roundness of the bow at the stem (figure 14).

As pointed out earlier, the seakeeping ability of a ship is relatively insensitive to moderate variations in hull form and not affected at all by local details. Whereas calm water behavior is markedly effected by these changes. Therefore the designer must be willing to make substantial changes in underwater form to produce the seakeeping qualities he desires. This fact is quite apparent when one considers the effect of length on seakeeping behavior of several geometrically similar ships. Figures 57, 58, and 59 illustrate the effect of ship length on pitch, heave, and slamming frequency. As can be seen pitch, heave, and slamming are all significantly reduced by large increases in length(L).

The other parameters used to measure seakeeping ability, such as deck wetness per hour, bow emergence, and frequency of propeller tip emergence are reduced with increasing length but this is more a function of increased freeboard and draft (normally associated with larger ships) rather than improved motions.

The effect of other hull form parameters B_x/T_x, C_p, C_x, L_{WL}/B_x, and Δ are shown in figures 60, 61, 62, and 63. The effect of varying B_x/T_x and holding C_p, C_x, and displacement

constant is a decrease in all motions with increasing B_x/T_x. Since both beam and draft were changed for the test results presented in figure 60, the larger B_x/T_x, the shallower the draft and hence the more frequent occurence of bow emergence.

When C_p is varied and draft is kept constant, the effect is to decrease all motions with increasing C_p if displacement, C_x, and draft are held constant. This is also true of frequency of bow emergence.

The effect of varying C_x and holding displacement, draft, and C_p constant is to decrease all motions with increasing C_x. This also pertains to frequency of bow emergence.

The effect of varying displacement-length ratio by changing beam and holding draft, C_p, and C_x constant is to reduce heave motions at speeds above a critical value with increasing displacement. Changing the displacement-length ratio by varying draft and maintaining beam, C_p, and C_x constant results in less pitch and relative bow motion with decreasing displacement but gives no improvement in heave. However, decreasing displacement results in a more frequent occurence of bow emergence because of the shallow draft.

FIGURE 57.
EFFECT OF LENGTH ON PITCH

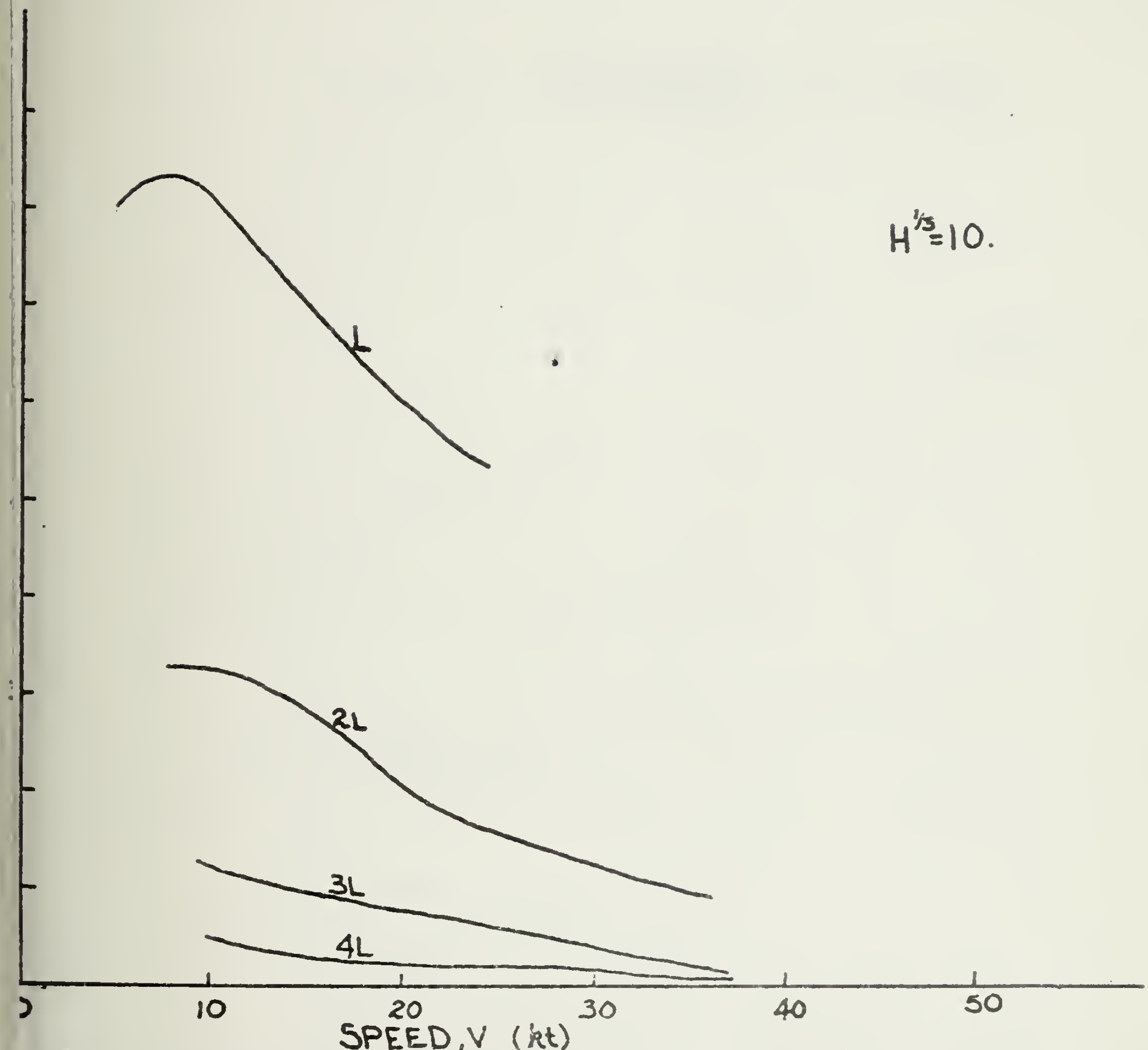


FIGURE 58.
EFFECT OF LENGTH ON HEAVE

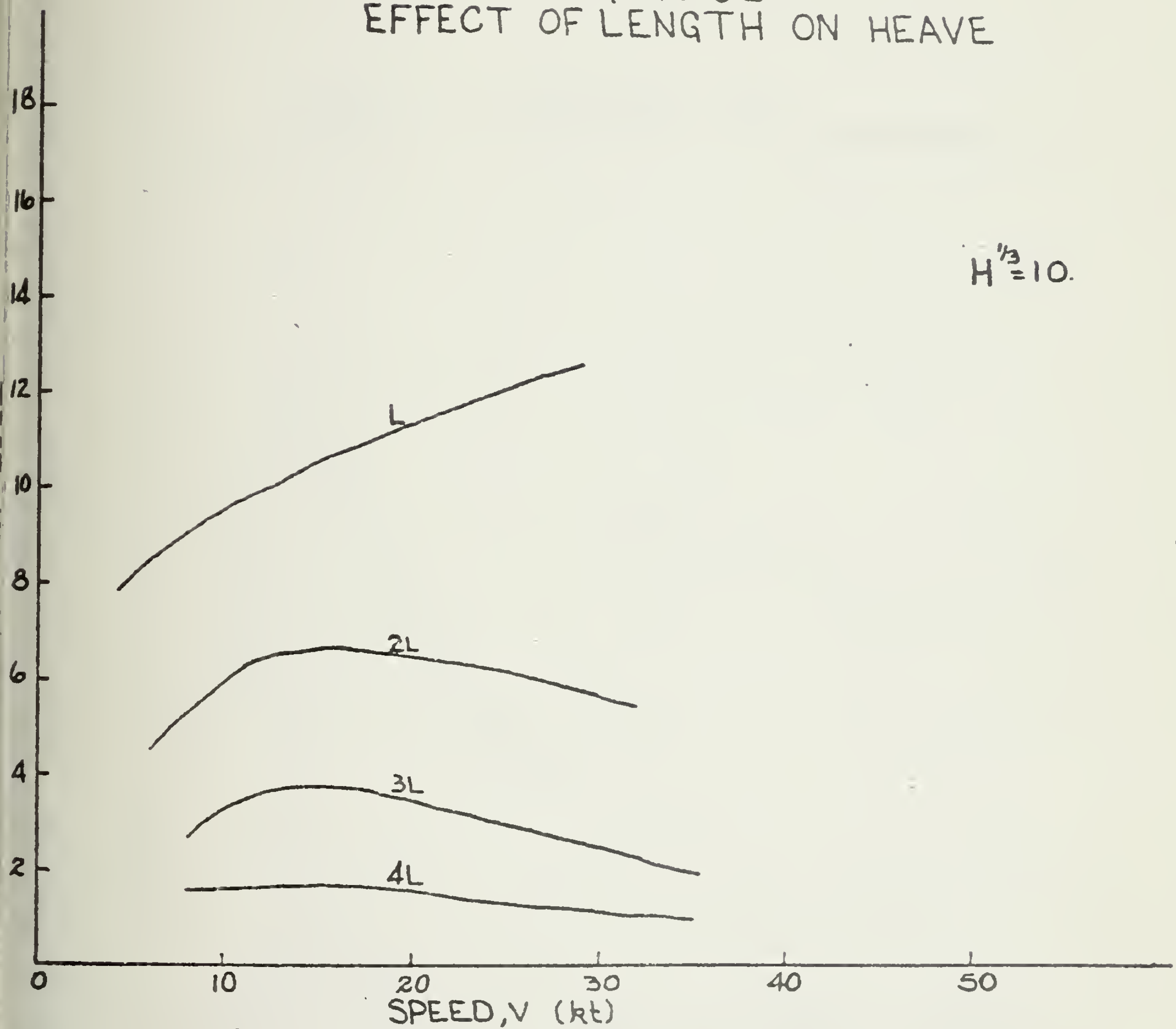
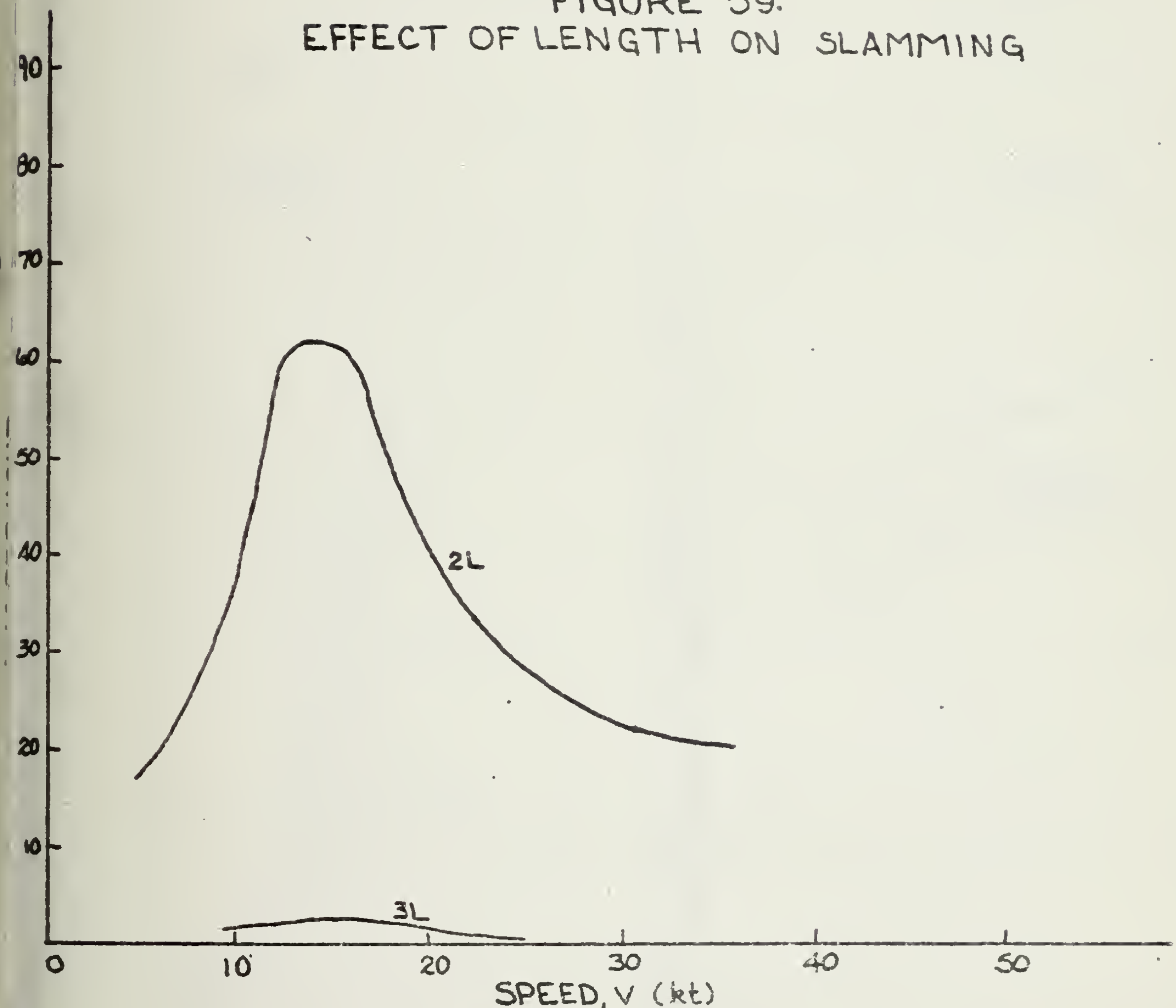


FIGURE 59.
EFFECT OF LENGTH ON SLAMMING



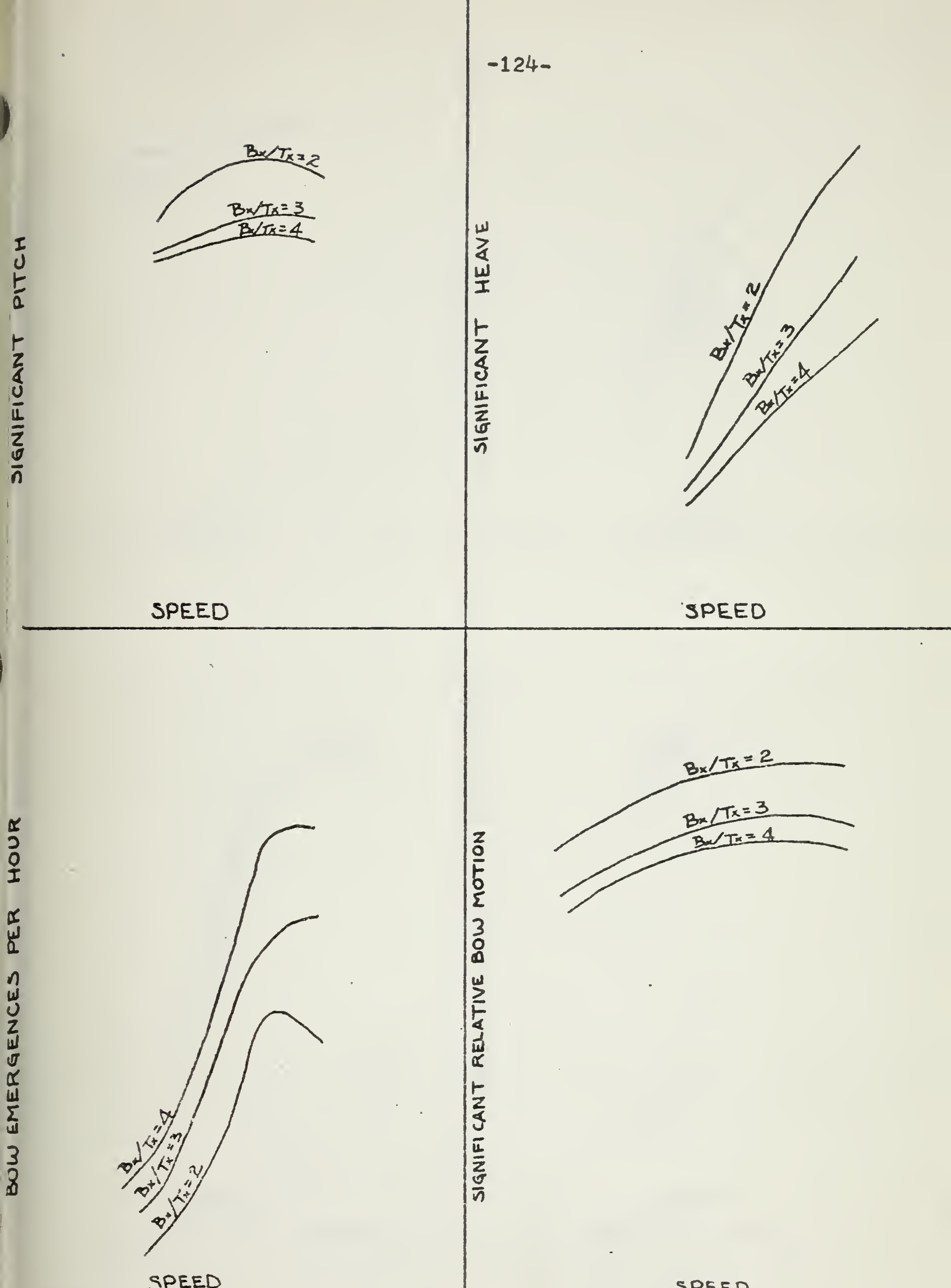


FIGURE 60. EFFECT OF B_x/T_x ON SHIP MOTIONS

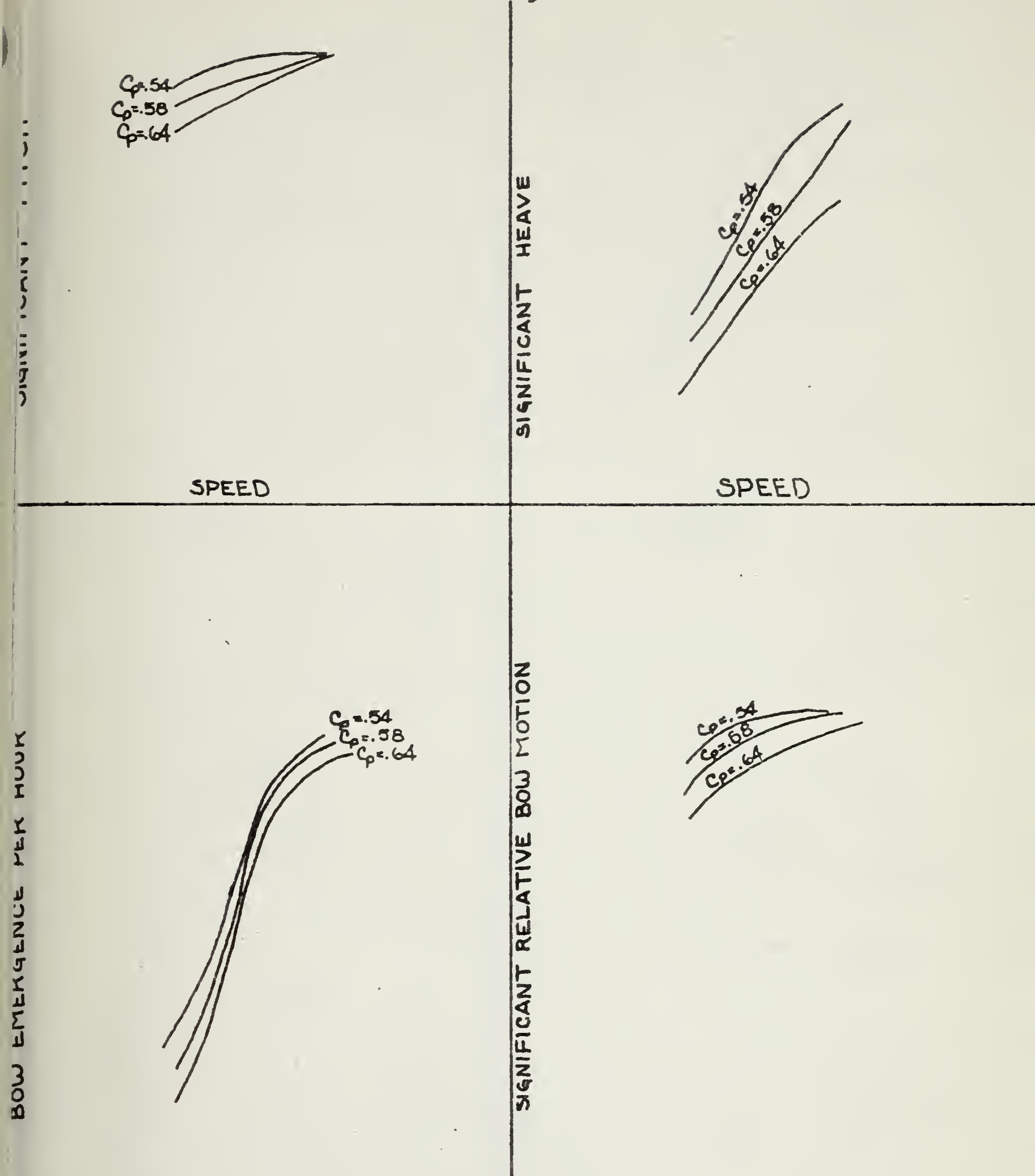


FIGURE 61. EFFECT OF C_p ON SHIP MOTIONS

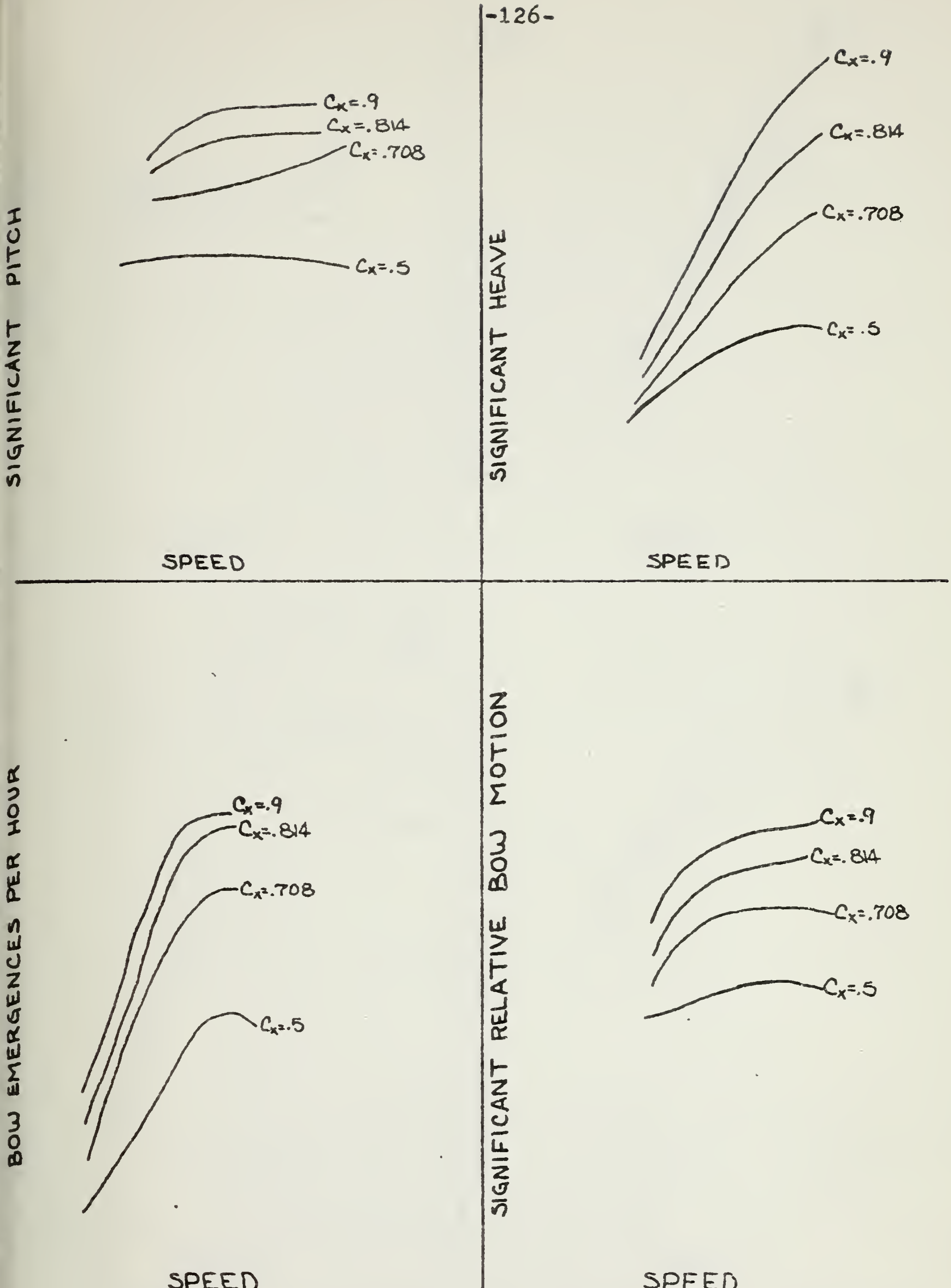


FIGURE 62. EFFECT OF C_x ON SHIP MOTIONS

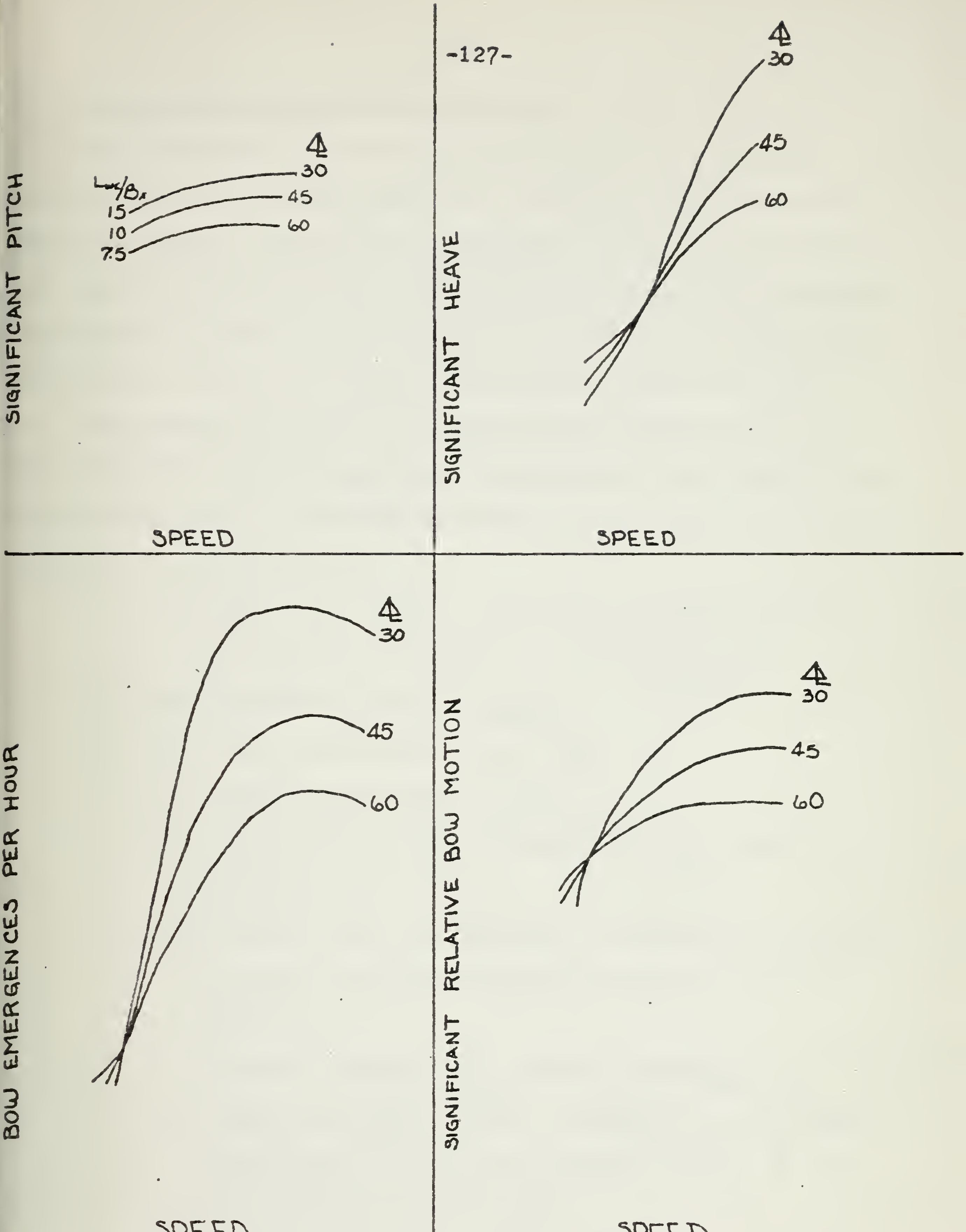


FIGURE 63. EFFECT OF ⩟ ON SHIP MOTIONS

4.5 Maneuverability(Tactical Diameter)

Ship turning and maneuvering performance is generally described by three basic definitive maneuvers referred to as: tactical diameter turning test, Dieudonne Spiral test, and the zig zag or overshoot test. The result of the tactical diameter turning test is the tactical diameter-length ratio. This ratio provides an easily used maneuvering quality comparison tool.

The tactical diameter is dependent to a large extent on the hull form and its appendages, particularly the relative size of the hull and its appendages. More specifically, the tactical diameter is a function of

1) Rudder area ratio - the ratio of rudder area to the product of length and draft($A_R/L_{WL}T_x$).
2) Length-beam ratio - L_{WL}/B_x.
3) Block coefficient - $C_B = C_p{\times}C_x$.
4) Draft-length ratio - T_x/L_{WL}.
5) Lateral area ratio - lateral(profile) area of ship/$L_{WL} \times T_x$.
6) Propeller area outside hull - propeller disk area outside of midship section divided by beam and draft.
7) Skeg area ratio - skeg profile area/$L_{WL} \times T_x$.
8) Propeller-Rudder overlap - amount of rudder span overlapped by propeller disc when rudder is at 35° divided by total span.
9) Speed-length ratio
10) Rudder angle

Some water must flow beneath a vessel during a turning maneuver. So those elements which make this under flow easier will reduce the tactical diameter. This is effected by reducing the draft, and consequently the draft-length ratio for a constant length, as well as providing a round bilge form by reducing C_x.

The other factor in a turning maneuver is the 'control surface' effect of the hull. The ship, after the initiation of the turn presents an angle of attack to the direction of motion and the hull acts as the wing of an airplane in flight. So those hull form parameters which provide greater lateral area (at a given draft) and slenderness will reduce the tactical diameter. Providing fuller ends to the ship by increasing C_p will increase the 'control surface' area and hence reduce the tactical diameter. The slenderness is improved by increasing the length-beam ratio.

The draft-length ratio has the greatest impact on tactical diameter, while the length-beam ratio has the least impact of the four parameters mentioned.

In comparing the maneuvering qualities of several ships it is difficult to assess the combined impact of all the hull form parameters without either model tests or actual sea trial data.

4.6 Summary

The influence of time, mission, the state of technology and design methodology are apparent from the previous sections. Nevertheless the influence of hull form in terms of the primary parameters on the other performance features is evident. Table 8 summarizes the effect of decreasing some of the hull form parameters on the other performance features. One can see that the penalty for increasing speed by decreasing Δ is a reduction in payload carrying ability and poor seakeeping performance. Whereas the penalty for increasing speed by selecting a larger C_p is also a decrease in payload carrying ability but the seakeeping performance is improved. The reduction in payload and propulsion weight associated with small values of Δ seems to be absorbed by structure. However the reduction in propulsion weight associated with decreasing values of C_p is absorbed by increase in structural and payload weight fractions.

The relationship between hull form and speed(or resistance) was shown in Chapters 2 and 3, and the relationship between hull form and other performance features in this chapter. The next chapter then applies all the previous discussion to the selection of a low resistance hull form and the estimation of the impact of that hull form on the other performance features.

TABLE 8.

EFFECT OF DECREASING SOME HULLFORM PARAMETERS ON OTHER PERFORMANCE FEATURES

PARAMETER	SPEED	PAYLOAD WGT FRAC.	STRUCTURAL WGT FRAC.	PROPULSION WGT FRAC	SEAKEEPING			STABILITY	TACTICAL DIAMETER
					PITCH	HEAVE	BOW EMERG PER HOUR		
Δ	↑	↓	↑	↓	↑	↑	↑	↑	↓
C_p	↓	↑	↑	↓	↑	↑	↑	↑	↑
C_x	↑	↑	—	—	↓	↓	↓	↓	↓
Ⓢ	↓	—	—	↓	—	—	—	—	—
T_w/B_x	↓	—	—	—	—	—	—	↑	—
B_x/T_x	↓	—	—	—	↑	↓	↓	↑	↑
NOTE: $V/\sqrt{L} > 1.6$									

5. A HIGH SPEED HULL FORM

5.1 Hull Form Selection

Reference 30 provides the only presently available tool to select low resistance hull forms in a short period of time. However by using reference 30, one is constrained to select hull form parameters within the data base. So an optimum may not be achieved.

As a starting point in selecting a low resistance hull form a value of 35 for the displacement-length ratio was selected. The reason for selecting this value is twofold; (1) as stated in Chapter 3 a low value of $\frac{\Delta}{L}$ is associated with low resistance at high speed-length ratios, and (2) 35 is the lowest value of $\frac{\Delta}{L}$ in the data base of reference 30 that the author felt could be used in predicting resistance with reasonable confidence.

Table 9 shows the range of values for each parameter and the values selected for $\frac{\Delta}{L} = 35$. In selecting the values an iterative process was used. Initially values were selected based on the correlation of each parameter with resistance at $V/\sqrt{L_{WL}} = 1.8$. Then the equations in reference 30 were used to calculate C_{TL}, which was compared to actual resistance data of some existing ships. With several forms having a predicted resistance at $V/\sqrt{L_{WL}} = 1.8$ lower than existing ships, a lines drawing of each of the forms was attempted. The most fair of the low resistance forms was then selected. Since a high speed hull form is desired, minimization of resistance at the

TABLE 9.

PERMISSIBLE RANGE OF PARAMETERS FOR SELECTING A LOW RESISTANCE HULL FORM WITH A DISPLACEMENT-LENGTH OF 35

PARAMETER	RANGE	VALUE
i_R	3°-14°	5°
i_B	2°-7°	3°
i_E	6°-8°	8°
C_x	.75-.8	.8
Ⓢ	7.9-8.45	8.0
L_{WL}/B_x	9.96-10.66	10.5
C_P	.5787-.6256	.6055
T_t/T_x	.1-.2	.16
f_A	.015-.13	.11
T_W/B_x	.5-.9	.85
$\overline{FB}/L_{WL}$	.49-.52	.517
f_B	0.	0.
B_x/T_x	2.9-3.6	3.6

TABLE 10.

PREDICTED VALUES OF RESISTANCE COEFFICIENT, C_{TL} 30

$V/\sqrt{L_{WL}}$	C_{TL}
0.8	17.6638
0.9	18.3143
1.0	19.2650
1.1	20.6482
1.2	22.4872
1.3	24.6964
1.4	22.1995
1.5	25.1007
1.6	27.5080
1.7	28.7251
1.8	26.1101

limiting speed-length ratio of reference 30 is consistent. It is noted that a low resistance hull form was found and not necessarily the least resistance form with $\triangle$ = 35 at $V/\sqrt{L_{WL}} = 1.8$.

The predicted values of C_{TL} at each speed-length ratio are shown in figure 64 and the lines drawing for the hull form in figures 65 and 66. It must be remembered that there is not a 100% confidence level in the predicted values of C_{TL}(Table 10). A model test is the best estimating technique short of building an actual ship but time limitations precluded a test.

5.2 Evaluation of the Hull Form

Two things are obvious from figure 64. The hull form selected by the author is definitely a relatively low resistance form at $V/\sqrt{L_{WL}} > 1.35$., and a relatively high resistance hull form at $V/\sqrt{L_{WL}} < 1.35$. At $V/\sqrt{L_{WL}} = 1.8$ one can see that a 17.5% reduction in C_{TL} could be obtained for three of the ships in the figure with the author's hull form. While at $V/\sqrt{L_{WL}} = 1.0$, at worst a 10% increase in C_{TL} is observed (Neal's hull form was a result of optimizing his regression equations[30] for $\triangle$ = 50).

To put these results in a form more useful for discussion the PF-109 was assumed to have been re-designed to the author's hull form with the same displacement. Table 11 lists the primary dimensions and coefficients. The most significant changes are the increased length and midship section coefficient, and the decreased draft.

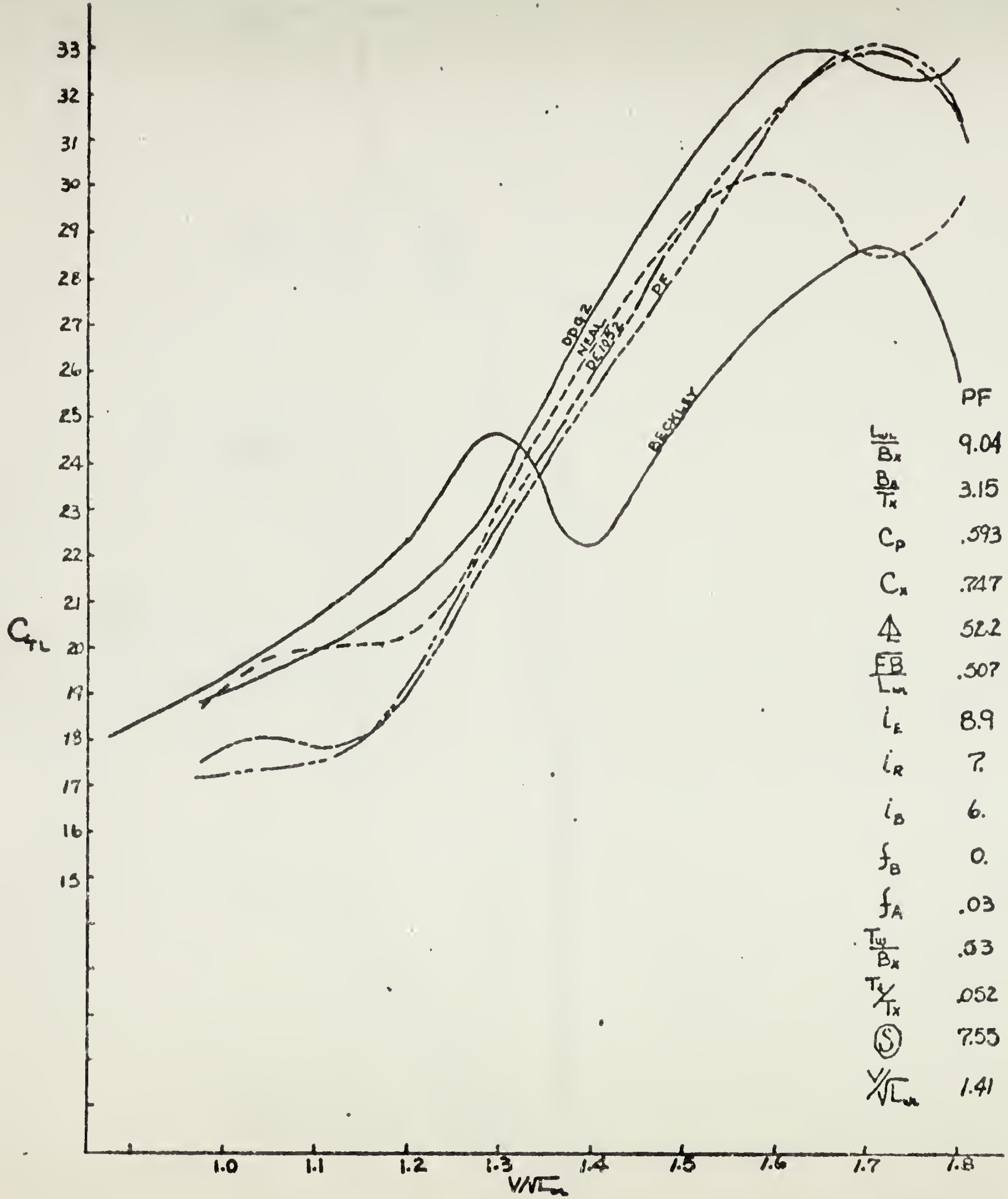
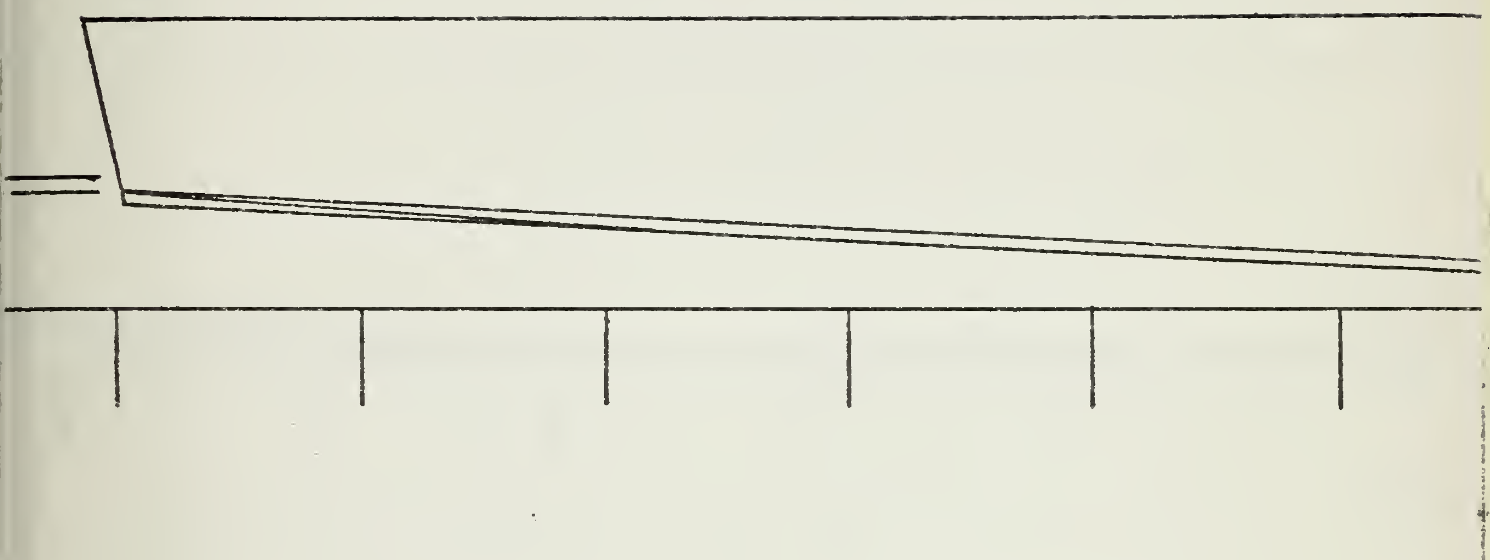


FIGURE 64.

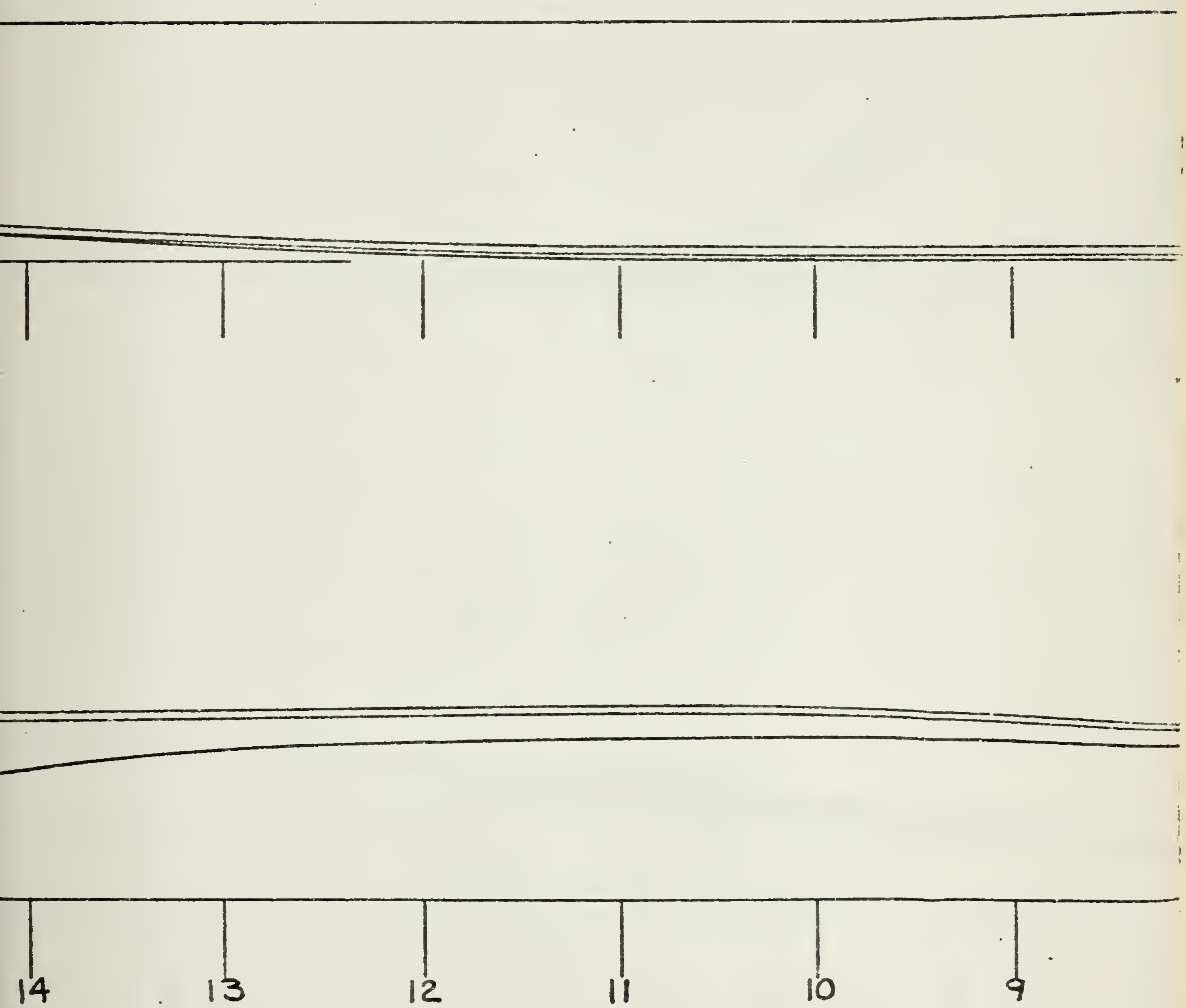
RESISTANCE COEFFICIENT, C_{TL} VS SPEED-LENGTH RATIO

	PF	DE1052	DDG 2	NEAL[30]	BECKLEY
$\frac{L_{WL}}{B_X}$	9.04	8.92	8.75	9.6	10.5
$\frac{B_X}{T_X}$	3.15	3.103	3.2	3.23	3.6
C_p	.593	.57	.636	.65	.6055
C_x	.747	.812	.835	.8	.8
Δ	52.2	53.88	61	49.78	35.
$\frac{FB}{L_{WL}}$	.507	.515	.5087	.51	.517
i_E	8.9	9.5	10.8	8.	8.
i_R	7.	6.5	11.5	10.	5.
i_B	6.	5.0	6.5	5.2	3.
f_B	0.	0.	0.	0.	0.
f_A	.03	.05	.068	.06	.11
$\frac{T_W}{B_X}$	.53	.585	.51	.65	.85
T_t/T_X	.052	.102	.194	.14	.16
S	7.55	7.489	7.083	7.64	8.
$V/\sqrt{L_{WL}}$	1.41	1.317	1.63	1.6	1.8

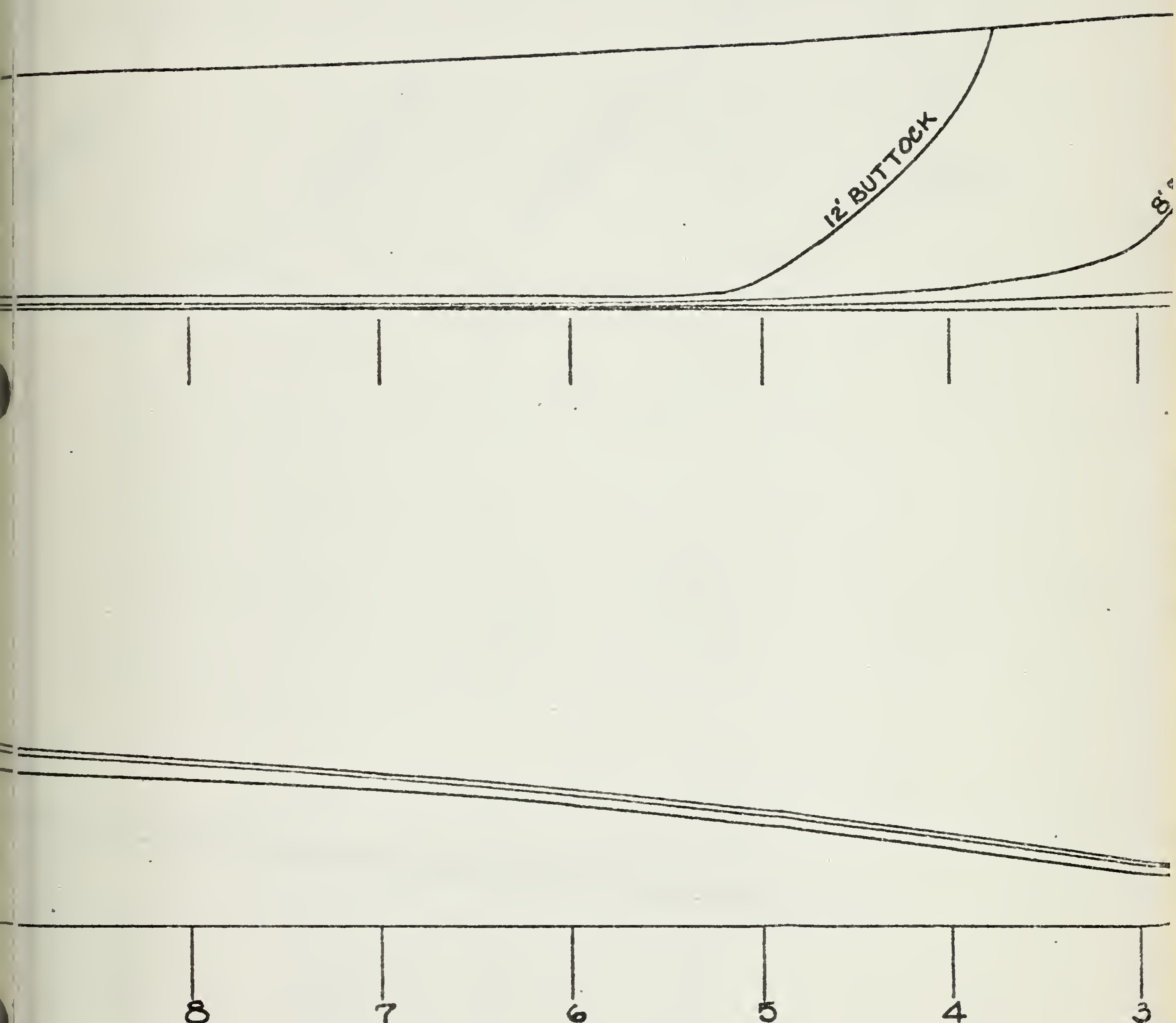


DWL
10' WL
5' WL
20
19
18
17
16
15

FIGURE 65. LINES OF AUTHOR'S



THOR'S PF



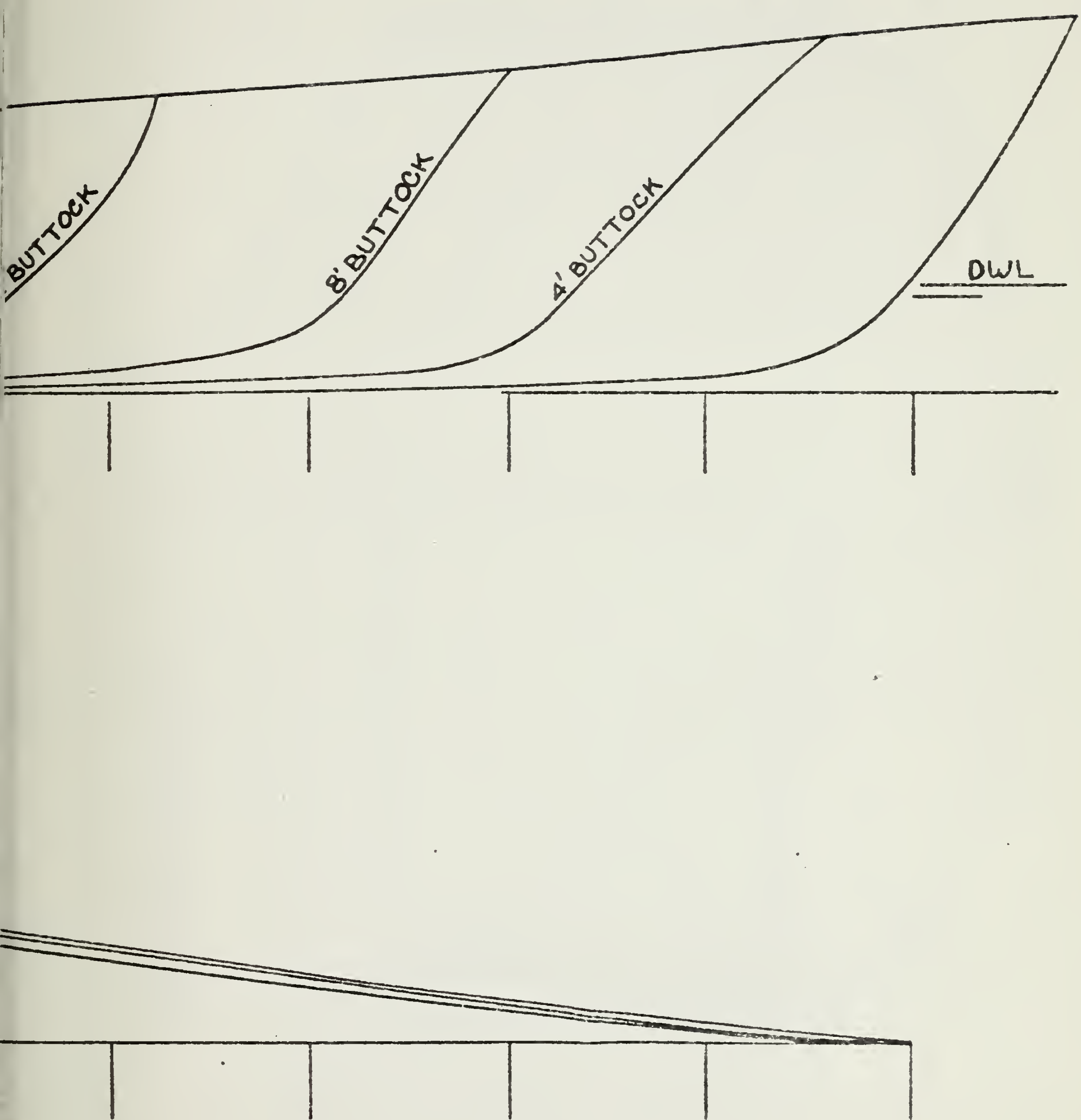

BUTTOCK
8' BUTTOCK
4' BUTTOCK
DWL
4
3
2
1
0

FIGURE 66.
BODY PLAN OF AUTHOR'S PF

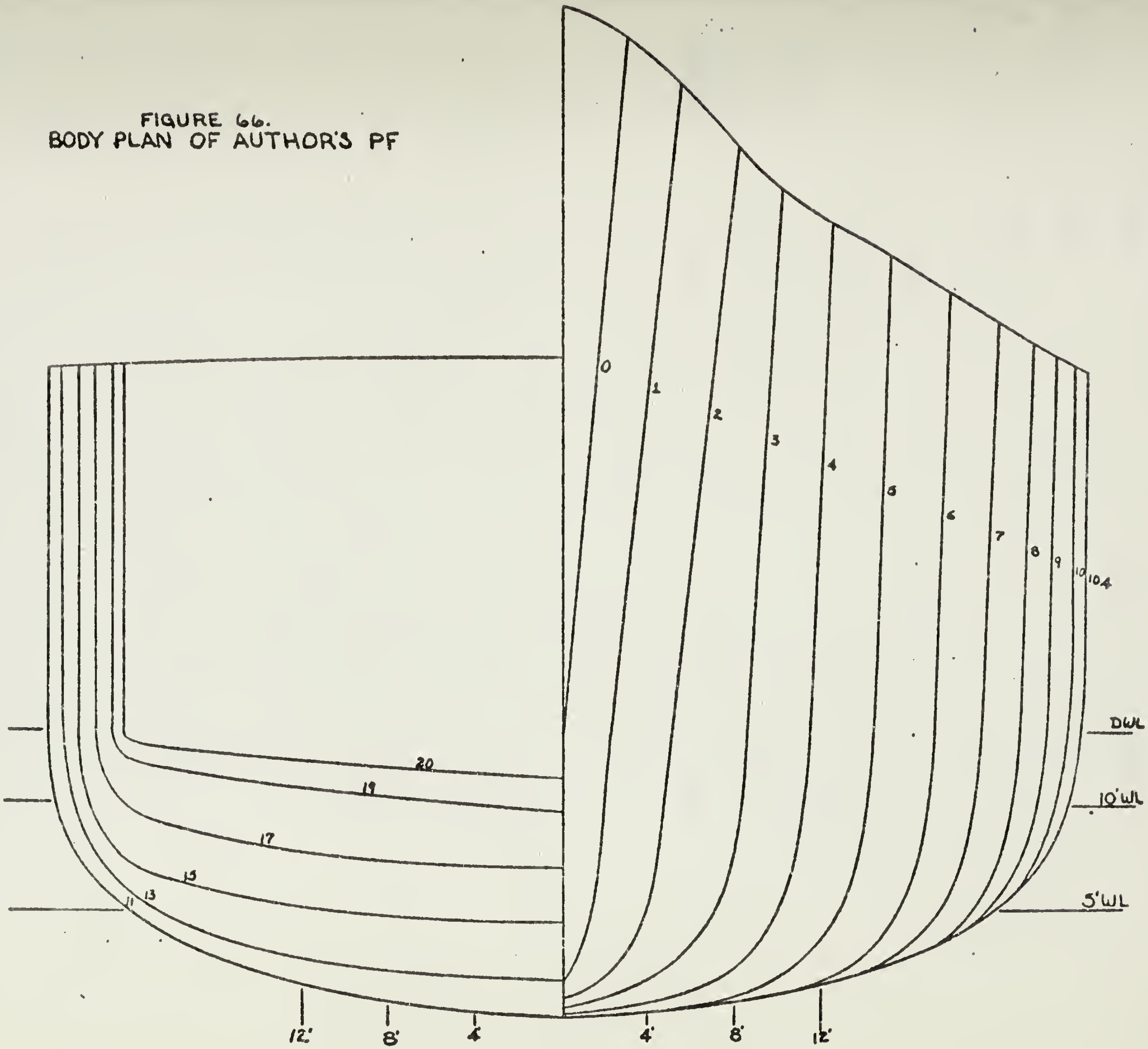


TABLE 11.

CHARACTERISTICS OF THE PF-109 AND THE AUTHOR'S PF

	PF-109	AUTHOR'S PF
Δ	3531	3531
L_{WL}	408	465
B_x	45	44.33
T_x	14.35	12.31
C_P	.593	.6055
C_x	.747	.800
$\overline{FB}/L_{WL}$	.507	.517
V_{design}	28.5	38.8
$V/\sqrt{L_{WL}}$	1.41	1.8

The PF-109 shows a wave interference hump at 22 knots (figure 64). As discussed earlier the wavelength of the transverse wave system generated by a ship increases with speed. Thus a transverse wavelength that is an integral number of ship lengths producing wave reinforcement or cancellation will occur first on the shelter vessel.

The effective and shaft horsepower of the PF-109 and the author's PF are plotted as functions of speed-length ratio and speed in figures 67-70. The effective horsepower curves for the PF are based on a Taylor Series approximation. A propulsive coefficient of 0.65 was assumed in calculating the shaft horsepower. The installed shaft horsepower of the PF-109 is 40000 hp. The ship is designed as having a 28.5 knot sustained sea speed at 80% full power, or 32000 hp. Since in figure 69 the EHP at 28.5 knots is 16000 hp., a propulsive coefficient of 0.5 was assumed by the designers; A remarkably low value for destroyers. Nevertheless for the sake of argument a propulsive coefficient of 0.65 was used by the author.

Assuming the same installed horsepower in the author's PF as in the PF-109 one can see(figure 70) that at full power (40000 SHP) the author's PF can travel 2.6 knots faster. This is an 8.1% increase in speed.

Alternatively, for the same design speed(which will be defined as 32 knots for the PF-109 in figure 70) the author's power requirement is 28500 hp. or 28.75% less than that on the PF-109.

FIGURE 67.
EFFECTIVE HORSEPOWER VS. SPEED-LENGTH
FOR PF109 AND AUTHOR'S PF

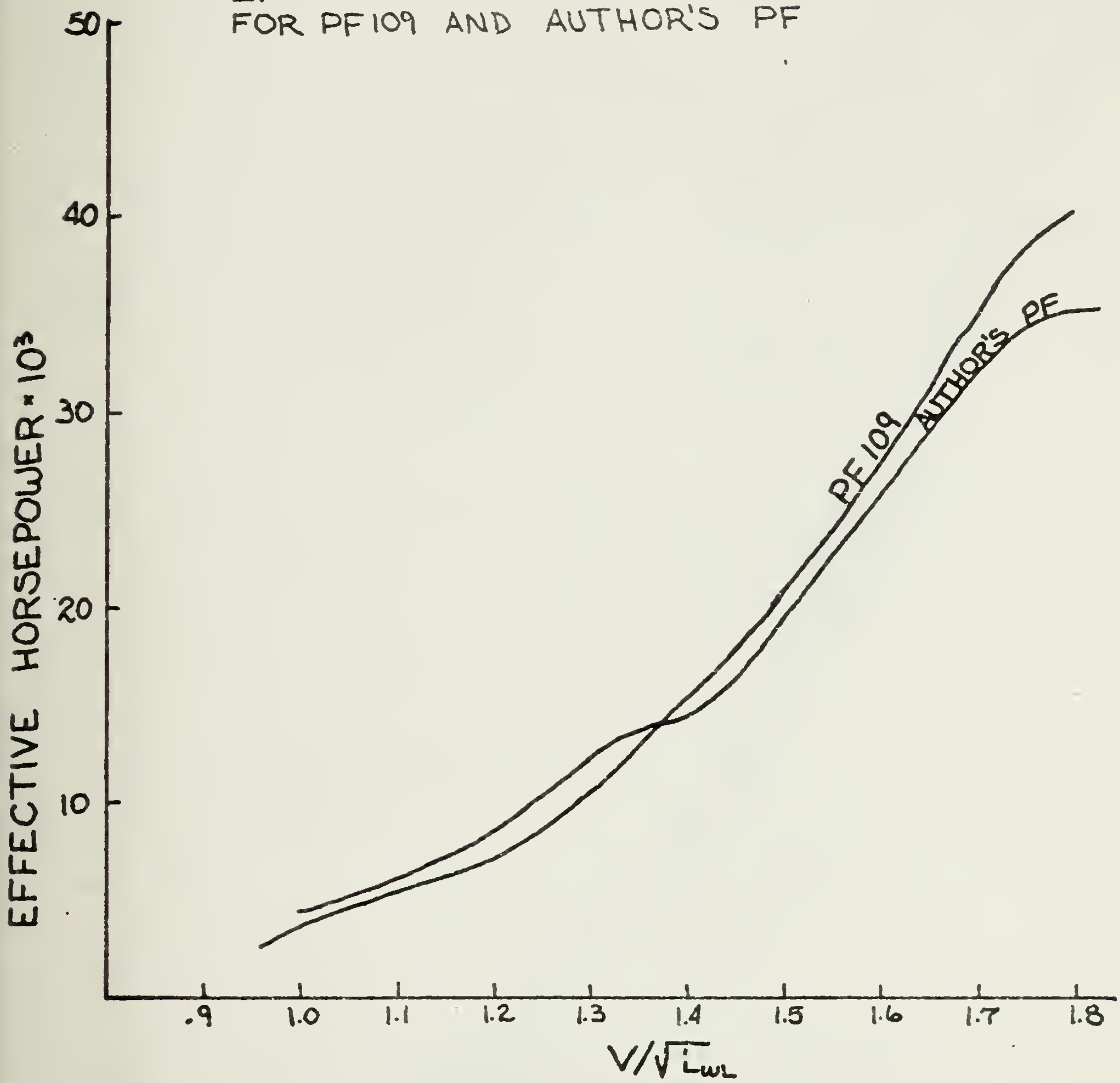


FIGURE 68.
SHAFT HORSEPOWER VS SPEED-LENGTH
FOR PF109 AND AUTHOR'S PF

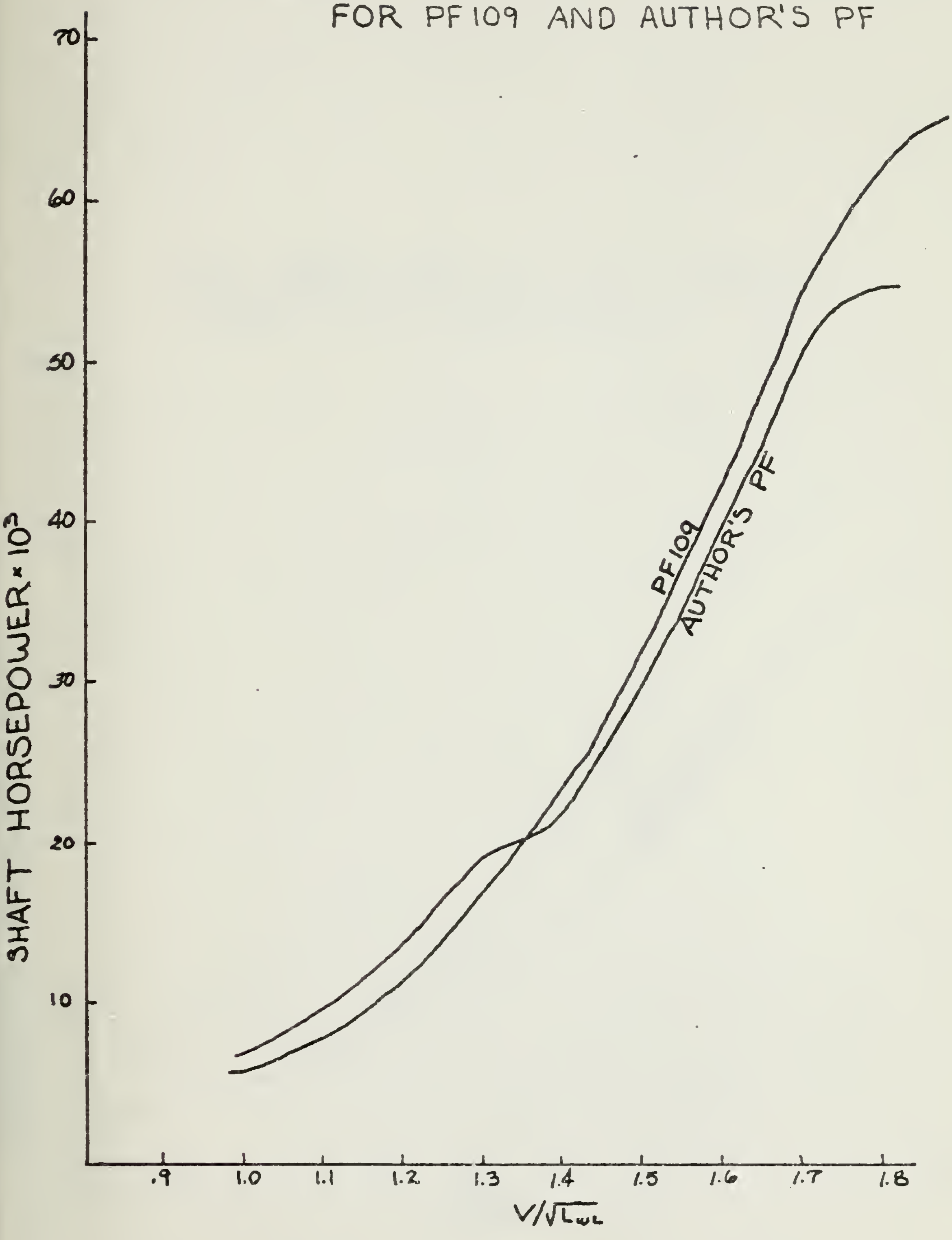
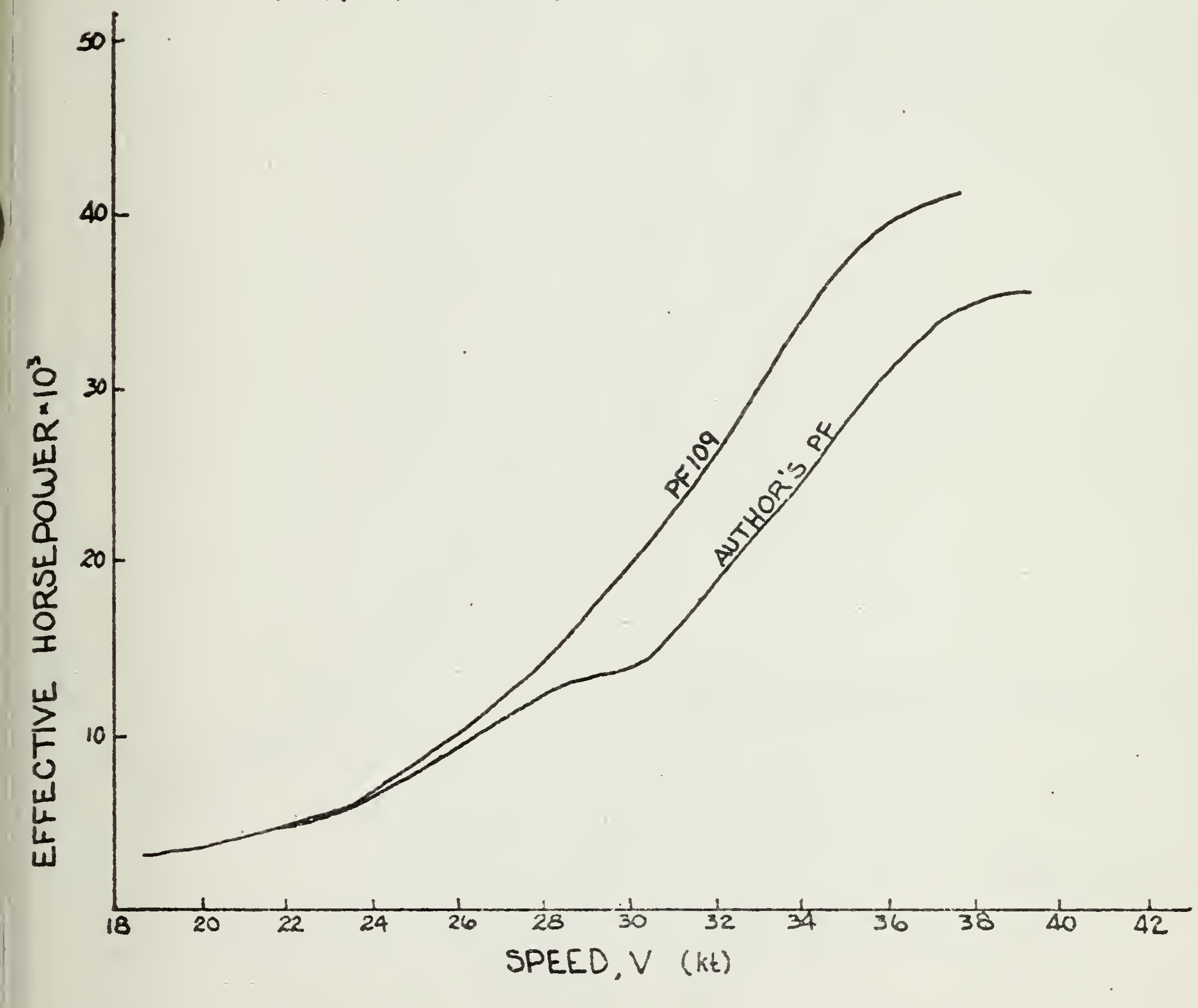


FIGURE 69.
EFFECTIVE HORSEPOWER VS. SPEED
FOR PF109 AND AUTHOR'S PF



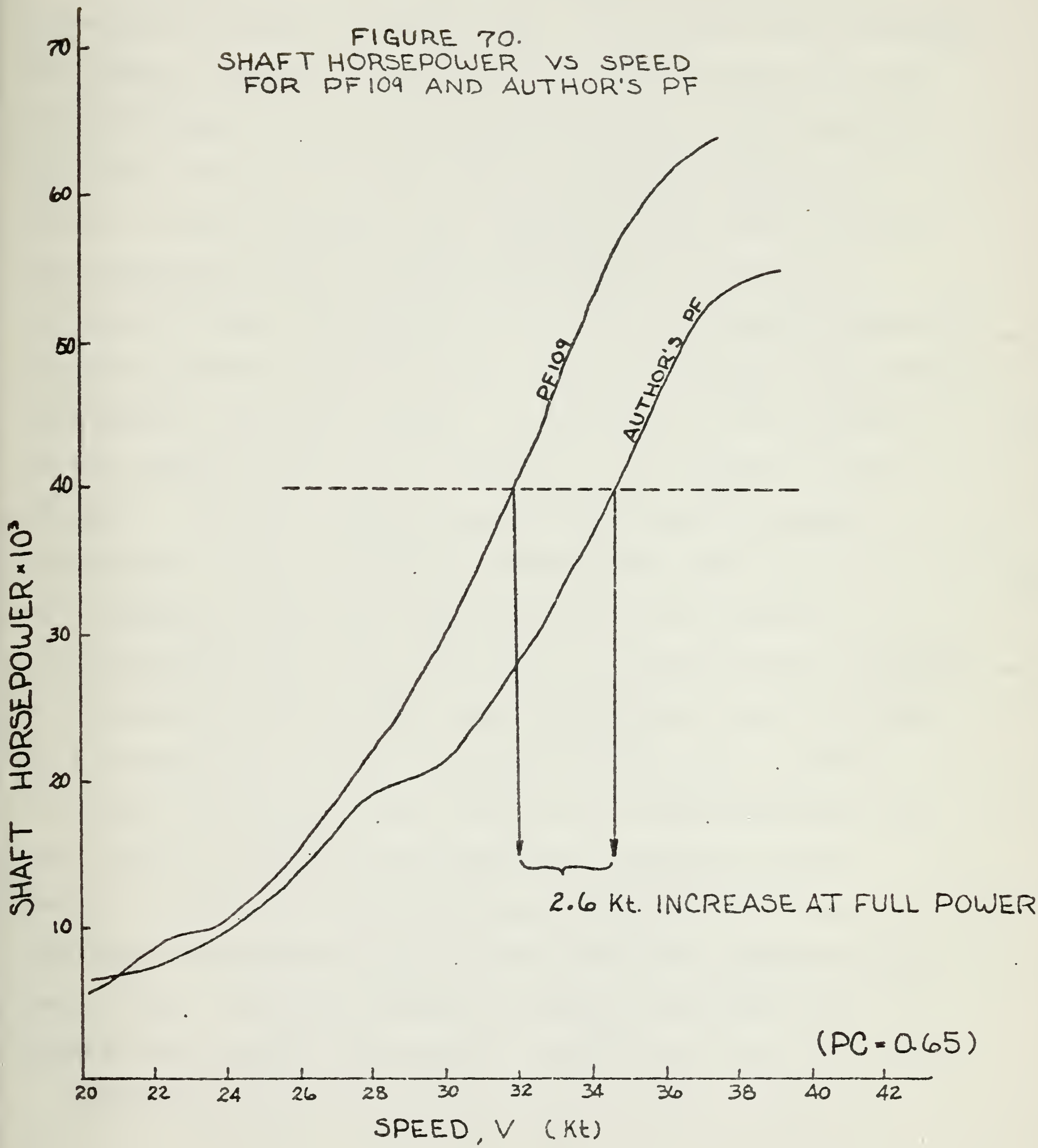


FIGURE 70.
SHAFT HORSEPOWER VS SPEED
FOR PF109 AND AUTHOR'S PF
PF109
AUTHOR'S PF
2.6 Kt. INCREASE AT FULL POWER
(PC = 0.65)
SHAFT HORSEPOWER × 10^3
SPEED, V (Kt)
70
60
50
40
30
20
10
20
22
24
26
28
30
32
34
36
38
40
42

What is the impact of the author's hull form and the alternative of retaining the 40000 SHP power plant? Since the displacement and power plant are the same, the weight group 2 fraction will remain constant(7.3%). The payload weight fraction was shown to decrease with decreasing values of Δ(figure 21). Since the beam has remained nearly the same and the draft has decreased two feet, the estimated reduction in metacentric height is one foot(figure 55). Therefore, the superstructure and the payload items contained therein could be retained. Assuming the same hull depth(30 feet), adequate volume exists for the same payload contained within the hull although a different arrangement would be necessary. However due to the fineness of the forward sections the usability of the volume is questionable. Also since Δ has decreased and depth remained constant the structural weight fraction(35%) must increase. The estimated increase in weight group one as a result of decreasing Δ (figure 32) is 10%, or a structural weight fraction for the author's PF of 45%. Hence the payload weight fraction will necessarily decrease somewhat. The auxiliary systems to support the payload would probably not change assuming the same number of personnel and associated personnel weights. Table 12 shows the estimated changes in weight fractions. Note that the personnel related weight has been separated from the payload. Hence the payload in Table 12 includes only command and control, and armament weights, and ammunition load.

Table 12 shows that an 8% increase in speed costs a 10%

TABLE 12.

EFFECT OF HULL FORM ON PERFORMANCE FEATURES

	WT.GR. 1.	WT.GR. 2.	WT.GR. 3.	PAYLOAD[2]	PERSONNEL	SPEED
PF-109	.35	.073	.395	.14	.10	32.[1]
AUTHOR'S PF-I	.45	.073	.395	.04	.10	34.5
AUTHOR'S PF-II	.45	.054	.395	.059	.10	32.

NOTE: I = 40,000 SHP plant, as in the PF-109

II = 30,000 SHP plant

1. Speed obtained with 40,000 hp. delivered to the water and a propulsive coefficient of 0.65.

2. Payload is defined in this table as weight groups 4, and 7.

reduction in payload and a 10% increase in structural weight.

Considering the impact of the hull form and the other powering alternative of installing a 30000 SHP power plant for the same speed(figure 70), the group 2 weight will decrease. Gas turbine power plants normally have a density of 15 lb./SHP. So the estimated reduction in group two weight is 67 tons. The new propulsion weight fraction then is .054. The structural and auxiliary weight fractions will be the same as for the other powering alternative. Thus payload increases to 5.9%, still less than PF-109 however. Hence a 25% decrease in power plant size costs, an 8.1% decrease in payload, and a 10% increase in structure.

Therefore in general the impact of using the low resistance hull form on weight fraction distribution is to increase structural weight and decrease payload for either powering alternative. Although more of the payload can be retained by decreasing the power plant size for the same speed.

Figure 70 shows that the endurance power requirement(at 20 knots) is essentially the same. Hence for the same fuel load endurance is not significantly impaired.

Reviewing figures 57-63, it is seen that pitch, heave, and slamming are reduced by the increased length. The low value of Δ will counteract the effect of length in reducing pitch and heave, though to a lesser extent. The shallower draft will result in more frequent bow emergence although the relative bow motion will be decreased somewhat due to the larger C_p.

It is expected that the tactical diameter will be reduced somewhat. As discussed in section 5.5 decreasing the draft-length ratio and the Δ will reduce the tactical diameter. The draft-length ratio has been reduced from .0351 to .0258 and Δ reduced from 52 to 35.

Thus by designing a long slender ship with easy curvature for low resistance through a reduction in residuary resistance at high speeds, it has cost a significant penality in payload as a result of increased structural requirements, and the seakeeping qualities are less satisfactory while maneuverability and stability have improved.

CONCLUSIONS

The focus of this manuscript has been on improving hull efficiency and investigating the impact of hull form on calm water speed and other performance features.

The proper design approach to achieve a low resistance hull form is to specify a tolerable range of hull parameters for good seakeeping qualities and then concentrate on the details of the hull form that minimize residuary resistance. The residuary resistance is sensitive to local details that result in changes in curvature in the principal lines in that they cause pressure disturbances that act as wave generating points. Thus high speed design calls for the least overall curvature in the lines. This results in long slender hulls with broad flat transoms.

But designing such a ship is not without its consequences. The volume limited nature of today's naval surface ships demands relatively short, full hull form. This is in conflict with the form needed for greater speeds. These full, inefficient forms require greater horsepower to achieve greater speeds. Installing this additional power would of course penalize other performance features, particularly payload. However a slender, low resistance form requires no increase in horsepower for greater speeds but still penalizes payloads since other demands must be met, such as increased structural weight. For the case of the PF-109, designing a more efficient hull form penalized payload 71% because of a 40% increase in structural requirements, while

speed increased only 8%.

Based on these results, though improvement in hull form design is quite possible the increases in speed obtainable are not worth the loss in effectiveness of the ship as a weapons platform.

It appears that present day designers have achieved a compromise of providing an effective weapons platform with reasonably good speed. Increasing payload with yet fuller ships will result in a severe penalty to speed and significant increases in speed will result in a severe penalty in payload.

RECOMMENDATIONS

1. A model of the author's hull form needs to be constructed and tested to verify the resistance as predicted by Neal's regression equations[30].
2. A design needs to be completed using the author's hull form to confirm the estimate of the impact of the hull form on the other performance features in section 5.2.
3. A cost analysis of the overall design is desirable.
4. A synthesis model similar to DD 07, but permitting greater constraint in hull form needs to be developed so that the operating community can more easily and adequately investigate and understand the consequences of demanding greater speed.

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